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# Corona-Solar Wind Coupling Review



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The prediction and forecasting of the particle and fields environment within the magnetosphere is of importance to the Air Force. In order to keep pace with the Air Force needs, methods of prediction must be considerably improved. Conditions within the magnetosphere are linked to conditions within the solar corona by the following chain: the coupling between the corona and the solar wind in the vicinity of the sun, the propagation of the solar wind from the vicinity of the sun to the vicinity of the earth, and the coupling of the solar wind at 1 AU to the magnetosphere. This report is a review of the present knowledge of the coronal-solar wind coupling and presents a brief description of problems that remain for the development of an enhanced capability to predict the level of geomagnetic disturbances. Recommendations for a 3-year and a 10-year research plan to address these problems is also included.


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Corona-Solar Wind Coupling Review

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## Introduction:

The prediction and forecasting of particle and field environments within the magnetosphere and ionosphere is of importance to the Air Force both in the planning of missions and in the control and amelioration of the effects of adverse environments on operating spacecraft. As Air Force space missions become more sophisticated the need to predict environments in space becomes more acute. In order to keep pace with the Air Force needs methods of prediction will have to be considerably improved. This report is intended as a contribution to that effort.

Conditions within the magnetosphere are linked to conditions within the solar corona by a chain of three links: the coupling between the corona and the solar wind in the vicinity of the sun, the propagation of the solar wind from the vicinity of the sun to the vicinity of the earth, and the coupling of the solar wind at 1 AU to the magnetosphere. Each of these three links can be studied separately. This report is a review of the first link, corona-solar wind coupling.

In order to determine which solar wind parameters are most important for prediction purposes a short preliminary review was undertaken of the propagation of solar wind from the sun to the Earth and the ways in which

geoeffective parameters changed during that propagation. A report on that preliminary survey is given in Appendix 1.

As a result of that study we here focus on questions of importance to the prediction of the primary geo-effective parameters; the solar wind velocity, v, and the north-south component of the interplanetary magnetic field, $B_z$. Other parameters influencing geomagnetic activity receive less attention. These include the magnitude of the interplanetary field, $|B|$, and its components in the solar equatorial plane Bx (along the Earth-Sun line) and By (orthogonal to $B_x$ and $B_z$ and positive in the direction of planetary motion), the density and perhaps the composition. The philosophy of the review is to concentrate on work relevant to the prediction effort. A complete review of the field of corona-solar wind coupling is beyond the purview of this report.

It is traditional to consider two different types of sources of solar wind, steady and transient (see figure 1). In the steady case the properties of the source region do not change significantly on a time scale long compared to the time it takes for the solar wind to travel from the sun to the earth, (i.e. several days). Coronal holes emit this type of wind. Steady state solar wind theories are believed to be applicable. Conversely, for transient solar winds, properties of the source change on time scales short compared to the sun-earth transit time of the plasma. Although there is recent evidence that this steady vs. transient dichotomy may not always be valid, the organization of this review will reflect that notion. In section 1 solar wind theories are discussed, section 2 reviews coronal

holes, section 3 deals with transient events, section 4 describes what little we know about the sources of the slow solar wind, and section 5 deals with specifications of conditions on a "source surface" that can be used as the inner boundary for interplanetary propagation models.

## 1. Solar Wind Theory

Theory of the solar wind is in a surprisingly unsatisfactory state considering the length of time the wind has been observed and the extent of the theoretical effort. Most early treatments of the solar wind problem assume a geometry for the coronal magnetic field and concentrate on predicting the velocity, density and temperature at Earth. The original simple Parker theory predicts a wind that is slower and hotter than observed (c.f. Hundhausen, 1972). The earliest modification that was attempted treated the wind as made up of two separate fluids, electrons and protons. These models predict a wind that is slower, denser and cooler than observed. Various attempts have been made to develop theories that predict the higher velocities and lower densities actually observed but to date there is no theoretical treatment of the problem that has received general agreement in the solar wind community.

During the 20 years that the solar wind problem has been studied there have been a number of approaches to the problem. Several properties of the system of equations are known (see for example review by Leer et al. 1982). The two fluid model studies indicated that energy had to be added to the wind at positions above the lower corona where the initial conditions of the theories are set. The position at which heat and momentum are added to the

solar wind is important in determining the response of the wind to these additions. The addition of heat in the region near the sun, in which the solar wind is subsonic, increases the mass flux that would be observed at the earth but has little effect on the velocity. Heat addition in the region in which the solar wind is supersonic does not effect the mass flux but increases the velocity at earth. The effects of an increase of momentum in the subsonic or supersonic regions is the same as those for velocity except that the effects are significantly larger than those associated with the addition of the same amount of energy by heating [Leer et al., 1982]

The effects of using different expressions for the heat conduction terms have also been studied. The earliest models used the heat conductivity term described by Spitzer which should be valid if the magnetic field is radial and the plasma is collision dominated. Although both of these conditions are expected to hold within the corona they will begin to fail as the solar wind leaves the vicinity of the sun. The effect of the non-radial interplanetary field on heat conduction has been studied by introducing a heat flux density given by the classical Spitzer value times the square of the cosine of the angle between the radial direction and the local magnetic field. In other studies two different forms of heat conduction were used, collision dominated near the sun and collisionless far from the sun.

Non-spherical expansion

The earliest models of a solar wind expansion treated the spherically symmetric case but the discovery that the fast solar wind came from coronal

holes implied that the wind expanded more rapidly than $1/r^2$. The effect of the more rapid expansion is to increase the acceleration close to the sun so that the point at which the wind becomes supersonic occurs closer to the sun than in the spherically symmetric case. However, there is little effect on the velocity at earth. An observation important for prediction was clarified by this study; i.e. if high velocity solar wind observed at earth is traced back to the sun assuming a constant velocity, the point back to which it is traced is close to the region of its actual source determined in other ways. This observation is not in agreement with simple spherically symmetric models because the initial acceleration is so slow in those models that the sun rotates a significant amount while the solar wind is rising out of the corona. Low velocity solar wind can not be as easily traced to its source regions.

## *Waves and Turbulence*

Another set of theoretical models that has been studied are models in which energy and/or momentum is added to the solar wind by interaction with waves. Barnes (see review, 1978) examined the effects of magnetosonic waves which are damped near the sun. Hollweg (1976) has studied the effects of Alfven waves in both adding momentum to the wind and in heating and accelerating helium in the wind. Unfortunately neither of these approaches yields satisfactory results for the velocities, densities and temperatures of the high velocity wind at earth.

In recent years the notion of turbulence in the solar wind has been receiving more attention. There are some differences between a collection

of waves and turbulence. It has been recognized for some time that the "Alfven waves" in space can not be represented as a linear superposition of small amplitude non-interacting waves and therefore they are not strictly Alfven waves. The observed waves have large amplitudes and are nearly non-compressible. The observed minimum variance direction of the magnetic field fluctuations is the direction of the Parker spiral magnetic field, which is then identified as the observed direction of propagation of the phase velocity. However the theoretically predicted direction of propagation of a linear superposition of non-interacting waves would be radial. Attempts to bring these two results into agreement have not been generally satisfactory. The spectra of the Alfvenic variations are power laws which suggests they are due to Kolmogorov turbulence, since theories of hydromagnetic turbulence predict that the spectrum for ideal incompressible inertial-range hydromagnetic turbulence consisting of a hierachy of Alfven waves will be a power law spectrum with an exponent of 3.5 (Kraichnan, 1965).

Several new approaches to the problem of the solar wind theory are being developed. It has been traditional to start the solar wind problem with a hot corona. One new approach considers the entire problem of heating the solar atmosphere (transition region, corona and solar wind) as a single problem. In the approach of Hollweg (1986) waves are assumed to originate in the photosphere and then propagate, producing the entire structure of the solar atmosphere. It is also assumed that the waves dissipate at the Kolmogorov rate. The qualitative results of Hollweg's analysis are encouraging in that he finds a steep temperature rise to a maximum coronal temperature of more than a million degrees, a substantial solar wind flux

and non-thermal velocities at the bases of holes. However the model fails in detail in that there was no value that could be found for the wave flux that would give realistic results for the wind velocities and coronal heating at the same time. Although this may mean that the model does not include the relevant physics of the problem it may also be due to the simplifying assumptions that had to be made. At any rate the notion that the entire solar atmosphere be considered as one problem is very attractive.

A different new approach has been taken by Pneuman (1983). He has developed a model of the solar wind which utilizes magnetic fields expelled by small scale magnetic reconnection as a driving force in addition to that provided by the gas pressure. In this model a magnetic element in the form of a loop is injected into the atmosphere by sub-photospheric forces, for example magnetic buoyancy. The loop is forced into an already existing ambient magnetic field. Stresses are produced by the ambient field which tend to pinch off the loop and cause the fields within the loop to reconnect so that a diamagnetic plasmoid is formed. If the ambient field decreases outward, as it would in a coronal hole, the plasmoid would be accelerated outward, thus increasing the speed of the solar wind. Pneuman investigated these processes using a simple isothermal wind model. He found that the velocity of the solar wind at earth could be significantly increased. Figure 2 shows the velocities at earth for different ratios of the mass flux carried by the diamagnetic elements to the total mass flux. The velocity can be about doubled at earth if all the solar wind was accelerated in diamagnetic plasmoids.

An important problem for the prediction effort is to produce a model which not only gives the correct values of the velocity, density and temperature of the solar wind as it rises from the corona, but also gives the magnetic field at the same time. Steinolfson et al., (1982) have recently attacked this problem by developing a self consistant model of fields and particles from a coronal hole. Their work is described in section 5 where the specification of conditions on the surface which serves as a source for interplanetary propagation models is discussed.

## 2. Coronal Holes

Since the beginning of this century it has been known that geomagnetic storms often recur each 27 days. i.e. the period of solar rotation as viewed from the earth. Although the recurrance period indicated that regions on the sun caused these storms, no specific structure was apparent on the solar disk that could act as a source for them. The mystery of these sources was solved in 1973 when soft X-ray observations from Skylab revealed large coronal dark regions or "holes" surrounding each of the solar polar regions and having major extensions that reached towards the solar equatorial regions. It was soon shown (Neupert and Pizzo, 1974) that the equatorward extensions of the holes were the sources of the high speed solar wind causing the impressive series of recurrent storms in 1973-1974. Since the Skylab era a great deal of work has been done to describe the properties of coronal holes and the solar wind they emit. In this section the current knowledge of the behavior of holes as they relate to geomagnetic activity is reviewed.

Observations

Holes can be observed in soft X-rays and XUV, by white light coronameters and in several lines of the solar spectrum. The methods of observations are of very different levels of accuracy and clarity. In table 1 information on each of the methods has been gathered to facilitate comparison.

The original observations of holes were made by the soft X-ray and XUV instruments on Skylab in 1973. They appear as large dark regions on the face of the solar disk with strong brightness contrasts between the holes and the rest of the corona. These Skylab holes had very sharp boundaries and there were X-ray bright points associated with them. About six months of data were collected before the X-ray instrument ceased to be operational. Data on holes has been less satisfactory since that time. The only high resolution full disk X-ray images have been provided by rocket flights at approximately 18 month intervals.

Holes can also be seen in the coronal white light observations in which they appear as dark alleys in the corona projected against the sky. At present they are being monitored from the Solar Maximum Mission and by earth based coronameters such as that at Mauna Loa. They were also observed by the Solwind coronameter but that was destroyed in 1985. These observations have the drawback for prediction systems of being on the limb. This is not a serious drawback for prediction if the holes are very stable as they were in 1973-1974. They are expected to be stable during the declining and minimum phase of each cycle. However, at other phases of the sunspot cycle

it can be quite serious since holes are not stable during the ascending phases or solar maximum. Stable long lived holes have been less evident during the declining phase of the cycle that maximized in 1979-1980 than they were in the previous cycle.

The behavior of holes in the 1960's and early 1970's has also been inferred from data on lines of magnesium, iron and helium that were observed from OSO-6 and OSO-7 satellites (Broussard et al., 1978). These data are taken against the solar disk and refer to various levels within the chromosphere and lower corona. Holes are also inferred in He 10830 which is monitored at Kitt Peak Observatory. This method of observation has the advantage for solar terrestrial relationship studies that the holes are observed on the face of the sun. However the accuracy with which hole boundaries can be determined is quite low. This is a very serious problem for studies of the relationships of specific properties of holes to parameters in the solar wind. Another possible indicator of holes exists in the iron lines. Altrock (1985) shows an example of a hole inferred from analysis of the Fe XIV 5303 A (green line) from Kitt Peak Observatory. These two methods of hole observation each have different drawbacks in that the He 10830 is not truly a coronal line but involves the chromosphere and is difficult to interpret, whereas the Fe XIV observations are low resolution. The use of the two types of observations together would perhaps form a much improved monitoring system over either of them alone (Altrock, personal communication, 1986).

## Properties of Holes Important to Solar Terrestrial Relations

The coronal holes observed by Skylab in 1973-1974 have become the standard to which holes in other periods are compared. These holes were very large, stable distinct features with strong contrast and sharp boundaries between them and the rest of the solar corona. Skylab hole characterization included almost rigid rotation, a nearly one to one association of holes and open solar magnetic field regions (Webb and Davis, 1985) and large low-latitude extensions of polar holes, with a strong correlation between low latitude holes and high speed solar wind streams observed in the ecliptic. Several studies have suggested these relationships are less clear for holes occurring during other parts of the solar cycle or in other cycles.

One of the most interesting observations made in the early days of hole observations was that holes did not take part in the differential rotation (Krieger and Timothy et al., 1975). In a recent paper Shelke and Pande (1985) have taken a new look at this question. They conclude that some holes do show a degree of differential rotation. They also seem to drift westward in the equatorial zone and eastward at latitudes greater than 10 degrees. In the equatorial zone the recurrence period of holes was close to 26.9 days. The recurrence time rose to 28.8 at the highest latitudes (40-60 degrees). This may be related to the changes of recurrence interval of the interplanetary sector structure with sunspot cycle phase reported by Svalgaard and Wilcox (1975).

An important problem for geomagnetic prediction is the birth and life history of holes. The formation of holes is an area in which a large amount of work is now being done but no clear concensus has yet evolved. Early in the study of holes it was noticed that there were small bright points seen in X-rays within the holes. Later research showed that these were regions of emerging magnetic flux. The relationship of these bright points to the growth and decay of holes is the subject of several recent studies. Davis (1985) studied X-ray bright points in equatorial coronal holes and found that the areal density of bright points within the holes increases linearly with time but that this is a local property and not related to the growth and decay of holes.

Studies have also been made of the evolution of holes during the sunspot cycle and a rather clear picture is emerging. From studies of geomagnetic storms we know that recurrent storms appear during the declining and/or minimum phase of each sunspot cycle (Newton, 1948) and it is therefore generally believed that coronal holes like those of 1973-1974, i.e. large polar holes with equatorial extensions also appear at these times in each cycle and, in fact, that the evolution of holes with the solar cycle observed since 1973 is typical of all cycles. The life time of those holes implied by geomagnetic activity is in the range of months or years. During the ascending phase the equatorward extensions of the polar holes disappear and are replaced by small low-latitude holes with lifetimes of a few months. Their rotation period is latitude dependent. The identification of these small holes as sources of the solar wind at earth becomes less secure (Sheeley and Harvey, 1981). The area of the corona occupied by holes also

decreases. Near sunspot maximum phase the new cycle begins with the change in magnetic polarity of the fields at the poles of the sun and the development of new stable holes. This sequence of events is undoubtedly related to the solar cycle in the configuration of the neutral sheet described in section 5.

The holes observed since 1974 are not as dramatic as the original Skylab structures. Kahler et al. (1983) found an apparant decrease in the brightness contrast between coronal holes and large scale coronal structure after 1974. Webb and Davis (1985) have analysed the rocket flight X-ray data for the years 1973 to 1981 and find a difference of a factor of 10 to 50 in average X-ray intensity with the minimum intensity ocurring in 1974. The intensity then rose uniformly until the last year of the data set, 1981. The contrast between the hole emission and the diffuse emission was also found to decrease. The association between open magnetic field structures predicted from photopheric fields and holes was also less clear (Levine, 1982). Open fields apparently emanated from active regions as well as from holes.

In a very interesting study Harvey et al. (1982) found that low latitude coronal holes contained three times as much flux near sunspot maximum as near minimum although the areas of the holes were about equal. It might have been expected that the solar wind field would reflect this increase in flux within holes by an increase in magnetic flux measured in the wind. Harvey et al. state that the interplanetary flux remained relatively constant but Slavin and Smith (1983) have reported that the solar

wind mean field increased after 1978 as shown in figure 3. The question of whether or not the increase in field intensity in space is related to the increase at the base of holes is an important one in solar terrestrial relations because of the relationship between geomagnetic activity and the interplanetary fields.

## 3. Transients

In this section we will deal with those events in which parcels of material or sudden increases of energy are injected into the solar wind. We include classical flare associated events, major events that may be associated with rising solar prominences (disparation brusque) and the more recently observed phenomena, coronal transients (coronal mass ejections). All of these transient events are related, although the exact natures of their relationships are not well delineated. We do know however that some of them are geoeffective phenomena. For example, major solar flares are associated with sudden commencement geomagnetic storms, although the relationship is far from one to one. Rising solar prominences are also statistically related to geomagnetic storms and it has been recently suggested that the storm-rising prominence relationship may be stronger than the storm-flare relationship (Joselyn and McIntosh, 1981). Coronal transients in general however occur at the rate of one or two per day and most of them do not cause noticeable geomagnetic activity. But transients accompany rising prominences and some major flares and may be the entity through which parcels of material are injected into the solar wind during those energetic events which, of course, do cause major geomagnetic storms. Hence studies of coronal transients are fundamental to the understanding of

corona-solar wind coupling responsible for geomagnetic activity.

## Observations

Solar flares are monitored from a world wide network of surface observatories of Hydrogen alpha emissions. The data are collected and a list of flares observed at each of the stations is compiled by the World Data Center A in Boulder, Colorado, and published as a series of monthly data reports. The reports contain information on the area, H alpha brightness, time of beginning and end, position and accompanying electromagnetic emissions. A world wide alert is issued by the NOAA Space Environment Laboratory when an event is detected on the sun that is expected to cause a major geomagnetic storm. This same network also monitors rising prominences. Prominence maps are included in the monthly reports of the World Data Center.

Table 2 lists the instruments used to observe transients. Coronal transients were first observed in 1973-1974 from the Skylab satellite. They were seen in the High Altitude Observatory's white light coronagraphs as regions of high density material rising through the corona. A schematic of a loop type transient is shown in figure 4. The loop gradually rises and expands until its outer edge leaves the field of view of the observing instrument and all that remains of the loop are the two rays corresponding to the loop legs. The bright legs sometimes persist for days. Material is rarely, if ever, seen to return to the corona. The high density structure is interpreted as outlining a magnetic structure within the corona.

Most coronal transients have been observed using white light coronameters where they are seen projected against the plane of the sky. This projection presents a problem for solar terrestrial studies since very few of the observed transients are moving in the direction of the earth.

Three coronameters observing transients have been flown in space, two by the High Altitude Observatory-National Center for Atmospheric Research (HAO-NCAR) and one by the Naval Research Laboratory (NRL). The HAO instruments were carried by Skylab and the Solar Maximum Mission (SMM). The NRL instrument was on the Solwind satellite. The HAO-SMM instrument, which is a coronameter and polarimeter, covers the corona from 1.8 $R_S$ to 5 $R_S$, and is still observing at the time of this report. In the data analysis the pictures are used directly and not differenced. The NRL Solwind instrument covered the range from 2 or 3 $R_S$ to 10 $R_S$. Solwind, with its operating coronameter was destroyed in 1985, ending the longest string of data on coronal transients that we had. The NRL data is differenced during data analysis, that is successive pictures are subtracted from one another, leaving a picture which shows only the changes that occurred. There are some interesting disagreements between the results of data analysis of the HAO and NRL data which have not yet been resolved. They involve such matters as rates of occurence and speed distributions and are probably due to differences in observation and analysis techniques.

Coronal transients at low altitudes in the corona are observed from the ground based HAO coronameter at Mauna Loa. Two instruments have been used, Mark 1 in 1965-1967 and 1969-1978 and Mark 2, from 1979 to the present.

Mark 2 observations cover the distance range from 1.2 to 2 $R_S$ and complement the HAO-SMM instrument so that together they cover the range from 1.2 $R_S$ to 5 $R_S$. The Mark 2 data is differenced in data analysis.

Recently several new methods of observing coronal transients in space have been developed, one using zodiacal light measurements from the Helios spacecraft (Richter et al., 1982) and the other using the NASA deep space network (Woo, and Armstrong 1981). The Zodiacal light experiments can observe transients out to 0.5 AU and detects disturbances at the point of nearest approach to the sun along the line of sight. Studies are also being done to evaluate the feasibility of using Fe XIV 5303 line observations to detect transients. No method of observing transients directly against the disk has been developed.

Flare - storm and prominence - storm relationships

A vast literature exists on the relation (and/or lack of it) of solar flares to geomagnetic activity. That literature will not be reviewed here in detail. Suffice it to say that some solar flares inject material and/or energy into the solar wind in such a way that geo-effective solar wind appears at Earth. Since only some flares do this many searches have been made to define the properties of the flares that cause storms. Among the most careful and dedicated workers in this field are E. Ruth Hedeman and Helen Dodson-Prince. Shortly before their recent retirement they produced some papers which I consider to be the most reliable documents on solar flare - geomagnetic storm associations. They rate each flare according to a

group of properties that are empirically the most closely related to geoeffectiveness. This rating they called the Comprehensive Flare Index (CFI). They also studied the geoeffectiveness of 269 major flares (i.e. CFI one or greater)(Hedeman and Dodson-Prince, 1981, Dodson-Prince et al., 1978). The flares were considered geoeffective if they were associated with a storm in which the maximum 3 hourly Kp was $\geq 5$. The derivation of the CFI is given below (from Hedeman and Dodson-Prince, 1980).

"Derivation of Comprehensive Flare Index (CFI)

To assist in the evaluation of the relationships between flares and geophysical effects, a Comprehensive Flare Index (CFI)based on the radio frequency and ionizing radiation of a flare as well as on its optical importance was developed by **Dodson and Hedeman** (UAG Report 14, 1971). The index is determined by five components which, when taken sequentially, constitute a crude profile of the electromagnetic radiation of the flare. The **sum** of the five components gives the Comprehensive Flare Index are as follows:

1. Importance of ionizing radiation as indicated by time-associated Short Wave Fade or Sudden Ionospheric disturbance; (scale 0-3) . . . . .
2. Importance of H flare (scale 0-3)
3. Magnitude of ~ 10 cm flux (characteristic of log of flux in units of $10^{-22}$ $Wm^{-2}$ $(C/S)^{-1}$).
4. Dynamic spectrum (scale 0-3; Type II = 1, Continuum = 2, Type IV with duration > 10 min. = 3).

5. Magnitude of ~ 200 MHz flux (characteristic of log of flux in units of $10^{-22}$ $Wm^{-2}$ $(C/S)^{-1}$).

The Comprehensive Flare Index can be determined for any flare for which the needed observations exist. Values of the Index have been derived and **published in Dodson and Hedeman**, UAG Reports 14 and 52, 1971 and 1975."

The result of the flare-storm study is seen in figure 5. Clearly a CFI $\geq$ 14 is a *reliable storm predictor*. However, there were only 7 such flares in the 4 years studied.

If our understanding of (and hence our ability to predict) the ways in which the sun causes geomagnetic activity is to progress we must go beyond statistical studies of associations and study the process through which this relationship is accomplished. In the case of solar flares the first question that comes to mind is whether or not actual material is expelled into the solar wind in association with a flare, or is it only additional energy that is emitted into the wind. The difference is the same as that between a bullet and a clap of thunder. Observations of solar wind properties associated with specific flares have been interpreted as indicating that actual material is expelled, at least in some cases (Hirshberg et al. 1970). It is still not known if material is expelled in every case. As far as the geoeffective parameters, velocity and southward magnetic field are concerned, both of these quantities reach very high values in flare associated events (Hirshberg et al. 1970). Velocities of well over 1,000 km/sec have been observed and southward fields of over 50 nT

are not rare. A problem arises in understanding the source of the huge southward magnetic fields. We have not yet established whether the southward field is induced by distortion of fields within the ambient solar wind or if the fields occur within the material ejected in association with the flare, i.e. the driver plasma.

Although this review focuses on the primary geoeffective parameters v and Bz, two other parameters that influence (or might influence) geomagnetic activity are mentioned in the introduction, density and composition. As far as density is concerned, its main effect is to compress the magnetosphere. The high velocity material from the sun associated with major solar flares is supersonic with respect to the ambient solar wind, which causes a shock to form in front of the driver gas. This shock, of course, causes the sudden commencement of magnetic storms. The other parts of the development of the storm (initial phase, main phase and recovery) are due to the structure within the solar wind that follows the shock. They are not due to processes within the magnetosphere set in motion by the sudden commencement. As far as the composition is concerned, the driver plasma often contains more than 10% helium by number or 20% by weight (Hirshberg, et al. 1970). However, no one has yet demonstrated a geomagnetic or magnetospheric effect of this high helium content.

Properties of Coronal Transients (coronal mass ejections)

The importance of coronal mass ejections (CME) to the problem of prediction of geomagnetic activity lies in the fact that geo-effective ejections are a subclass of coronal transients so that studies of mass

ejections in general will illuminate the processes involved in producing geomagnetic effects. Coronal transients form an extremely important new source of data on solar terrestrial relationships.

Thousands of mass ejection events have been observed since they were first detected in 1973-1974 and studies of their properties have begun to provide descriptions of the phenomena. However, these descriptions are far from complete. The emerging picture of coronal transients is reviewed in some detail here to help identify outstanding problems the solution of which will aid in the effort to develop a more accurate prediction capability.

Statistical studies of large numbers of transients have been carried out to give a picture of their general properties. There are some differences between the exact results from the NRL and HAO instruments which, as mentioned earlier, are probably due to differences in both the instruments used and the methods of analysis. However, both groups agree that the rate of occurrence is about 1 or 2 per day. They occur at all position angles relative to the sun's *equatorial plane* (Sheeley et al., 1980, Hundhausen et al., 1984) and material is rarely if ever observed to return to the sun. The velocities range from 50 km/sec to almost 2,000 km/sec (Sheeley et al., 1982). The lower limit of 50 km/sec may well be due to difficulties in observing slower transients. The maximum velocity that had been observed in 1982 was 1,825 km/sec. Howard et al., (1985) studied a large sample of data and found an average velocity of 470 km/sec with an average mass of $4 \times 10^{15}$ grams ejected per event. This velocity is about the same as that reported for the 1973-1974 period (Gosling et al., 1976 ).

It is estimated that about 5% of the mass flux at earth comes from coronal transients. This may well underestimate the importance of transients to geomagnetically disturbed periods. The distribution of geo-effective parameters in transients seen at Earth is unknown. However, since the direction of the magnetic field within them is not constrained by symmetry to be in the solar equatorial plane (as it is for a spherically expanding solar wind) coronal transients may contribute to geomagnetic activity out of proportion to the contribution they make to the solar wind mass flux. The average mass and energy for all transients may be compared to the average mass of $3.5 \times 10^{16}$ grams and energy of $1.4 \times 10^{32}$ ergs for material associated with interplanetary shocks at earth (Hundhausen, 1972).

Work has also been done on defining morphological classes of transients and finding their properties as a function of class. Munroe and Sime, (1979) identified three basic types of CME found in the Skylab data set, loops, amorphous clouds and "other". Occasionally a transient appears as a halo around the entire solar dish. This is due to a geometric effect and is caused by the transient being emitted in the direction of the observer (c.f. Jackson, 1985). Some 26% of the Skylab sample were loops. Howard et al., (1985) refined the classification system to 10 categories and 3 "importance" classes. They found only 1% of their sample were complete loops. It is not known whether or not the defined morphological categories correspond to physically important distinctions. The "importance" classes were based on event intensity. The events with high importance in general had high velocity and were about 10 times as massive as the low importance events. On average half the events were minor. The occurance frequencies from the

HAO-SMM instrument and the NRL instrument are not the same and more work needs to be done to understand these differences (Hundhausen, personal communication, 1985).

The occurrence rate of all coronal transients together shows little if any clear solar cycle dependence (Hundhausen et al., 1984). The number of high velocity events has a more complex solar cycle behavior. Howard et al., (1985) studied the statistical properties of events with speeds of at least 800 km/s and there was a striking change in occurrence rate from about 0.05 per day in 1979 to about 0.17 in late 1982. Sunspot maximum occurred in late 1979 - early 1980 but the sunspot number changed little between 1979 and 1982 and what changes there were showed no correlation with the occurrence frequency of high speed transients. On the other hand, Hundhausen (personal communication) finds a marked decrease in the number of high speed events as solar minimum is approached.

Since high and low speed CME show a different solar cycle variation it is interesting to see if these two catagories differ in other respects. MacQueen and Fisher (1983) described mass ejections as falling into one of two patterns:

1- Events that appear at high speed in the corona between 1.2 and 2.2 $R_s$. These events have been accelerated below 1.2 $R_s$ and show only small further acceleration above 1.2 $R_s$. They are associated with solar flares.

2 Events which appear at low speed at 1.2 $R_s$ but are observed to

accelerate over a wide range of heights as they pass through the corona. These events are associated with rising prominences.

Munroe and Sime, (1979) found that 70% of the Skylab CME's were associated with eruptive prominences but only 40% were associated with flares, the latter being higher speed events.

The observation that coronal transients are commonly still being accelerated at coronal heights greater than 1.2 $R_S$ has important consequences for both theory and modeling. The physical processes responsible for the acceleration are a subject of active study. One suggestion is that the force that acts on the transient within the corona is a hydromagnetic buoyancy effect (Yeh, 1985). Pneuman (1983) also treats the effect of magnetic fields on acceleration of coronal material into the solar wind, as described in section 1 on theory. Accurate modeling of transients within the corona must wait for determination of the behavior of the acceleration and identification of the mechanism.

A specific morphological class of CME's was studied by Illing and Hundhausen (1986). They collected a sample of 80 well observed events each of which consists of 3 parts (see figure 4). First there is a bright loop which they interpret as material swept up from the corona. Below is a bright center that is probably prominence material. Between the two there is a relatively dark region that probably contains the material that is normally seen as a dark region lying over a prominence. Figure 4 shows a

schematic of the positions of various structures within one of these events as a function of time. The coronal acceleration of the prominence and the differing velocities of the parts is seen. About 65% to 80% of SMM transients had a bright outer rim and 1/3 to 1/5 of SMM transients had a dark region. There is also some evidence for extremely slow events with velocities as low as 20 km/sec.

An important observation concerning the association between transients and the associated flares is that transients have been seen to begin to rise before the flare started. This observation has implications for an interesting problem. There are believed to be two distinct ways in which material is accelerated into the solar wind, the quasi-static expansion processes discussed in Section 1 and acceleraton during magnetic reconnection events associated with flare onsets. A study of 100 years of geomagnetic activity (Feynman, 1982) has been interpreted as suggesting that only one acceleration method is involved, except perhaps occasionally. The observation of the pre-flare transient acceleration shows that the energy release mechanism that produces the H alpha flare is not required for the onset of the associated CMEs. A further observation, that the feet of the transient loops (figure 4) remain open for many hours or days following the event, suggests that these structures remain the source of solar wind for extensive periods. This also is in agreement with the idea that transient associated and hole associated wind are accelerated by the same mechanism. Furthermore, Jackson and Leinert (1985) have studied the interplanetary data from the Helios zodiacal light experiment for two mass ejections, May 7 and May 24, 1979, and found that the May 7 ejection had a radial extent of 0.3

AU and took 1.5 days to cross the inner Helios photometer field. They conclude this material was continously being emitted from the inner corona. in agreement with the early findings of Hirshberg et al., (1970), and Hundhausen, (1972) from characteristics of the post-shock flow in interplanetary events. Even more impressive is the finding that for the May 24 event the sun continued to expel mass through the Helios field of view for "many days" so the total injection during the period of persistent features ("legs") was greater than that from the rapidly moving features that appear early in the event.

Studies have also been made of the relationship between coronal transients and a variety of phenomena related to prediction of solar-terrestrial disturbances. Sheeley et al., (1985) investigated associations between transients and interplanetary shocks observed at Helios. He found that 72% of the shocks could be associated with transients and 61% of the transient-shock events also had associated X-ray events. The mean duration of the X-ray events was 5 hours. Ten 1982 events had Sun-Helios mean speeds of 1,190 km/sec. Nearly all the well identified transient-shock events involved near-equatorial transients with angular widths greater than 40°. Kahler et al., (1984a,b) have studied the relation of transients and Type II bursts. It had been believed that type II bursts were produced in front of mass ejections (at shocks), but difficulties became apparent. They found that about 1/3 of all type II bursts were not associated with transients and that there are fast transients without type II. There is no generally agreed upon model to explain this behavior. Wagner and MacQueen, (1983) suggests a model in which the shock that produces the type II bursts is not

caused by the transient but by the flare. This suggestion was tested empirically by Robinson (1985) but the results were inconclusive. Steinolfson (1984a) did a simulation of a transient with type II and obtained agreement with observation but he found that the large velocities of the type II emission region do not directly correspond to either material or shock motion. These studies are important to solar terrestrial prediction techniques because the high source velocities are often attributed to shocks near the sun and then imply an excessive loss of shock speed between the corona and the point of shock observation in space.

The relationship of transients to structures observed in the solar wind near earth has also received attention. Two structures have been proposed as candidates, non-compressive density enhancements (Gosling et al., 1977) and magnetic clouds (Burlaga et al., 1982). (These two types of event may be closely related or even different aspects of the same event.) Testing of these hypotheses is underway (Wilson and Hildner, 1984) but much further study is needed before a convincing case can be made for either structure or for any new candidate that may be proposed. In addition, the contribution that the "every day" CML (in contrast to the rare very high speed CML) makes to geomagnetically effective solar wind must be investigated.

## 4. Slow Solar Wind

Less work has been done on the sources of the slow solar wind, at least partly because at Earth parcels of very slow wind (if any) will have been overrun by parcels of higher velocity wind during Sun-Earth propagation.

Developing a description of the behavior of the slow wind is a necessary first step in comparing observation with theory and finding sources. Feldman et al., (1977) investigated the basic parameters of wind with velocity less than 350 km/sec at Earth and found an average proton density of 12 $cm^{-3}$, temperature of $3 \times 10^4$ K, and helium abundance of 3.8%.

Marsch and Richter (1984b) report on the parameters of wind at the Alfven critical point. They use Helios data in the distance range from 0.3 AU to 1 AU to infer the solar wind parameters closer to the sun. For example for wind of velocity less than 400 km/sec the Alfven critical point was at 34 solar radii and the density was 4,000 $cm^{-3}$. Borrini et al., (1981) examined the helium abundance variations as a function of time from sector structure boundaries and found a low velocity low helium abundance region about the sector crossing. On this basis they suggested the slow wind came from the region of the coronal streamer that marks the sector boundary (or equivalently the interplanetary neutral sheet) in space. Steinolfson, (1984b) has modeled the solar wind expansion from a dipole in such a way that the wind and magnetic field are consistent with one another. They found that a helmet like structure appeared at the dipole equator and the wind velocity was depressed in that region. Freeman and Lopez (1985) have studied the low temperature solar wind from Helios plasma data. The low temperature wind is, at the same time, the low speed wind. They normalize the data to 1 AU and compare with predictions of the two fluid solar wind theory. They extrapolate their data to imply the temperature that would be observed for a minimum solar wind velocity which they take to be 250 km/sec. They get a temperature of $4.4 \times 10^3$ K and suggest that this

is in reasonable agreement with the 2 fluid model without further heat addition. This is an interesting approach and should be pursued further.

## 5. Source Surface for interplanetary propagation

In sections 2, 3, and 4 the discussion of corona-solar wind relationships was organized according to problems centering on acceleration mechanisms within the corona, that is, fast wind from holes, wind from transient sources and slow wind. In this section the problem of prediction will be discussed from another point of view, that of the source surface required for interplanetary modeling programs (see appendix). These programs typically require initial conditions specified at some surface near the sun. This source surface is chosen so that no further solar wind acceleration takes place beyond it and the magnetic field is radial at the surface. (Note that this use of the term "source surface" differs from the usual use which refers only to a surface on which the magnetic field is radial.) If the parameters of the solar wind are known on this surface (and the position of the surface is also known) then, in principal, the prediction of the solar wind parameters at earth is a problem of interplanetary propagation only. The interplanetary propagation problem is briefly reviewed in appendix one. The major lack in the interplanetary model is the inability to model (even in the statistical sense) the magnetic field turbulence, i.e., the production of waves resulting in a southward magnetic field component. These problems are not the subject of this review however, since they occur in the interplanetary region. In this section we evaluate our ability to determine the initial conditions for the source

surface.

The large scale structure of the interplanetary field is dominated by a wavy sheet of current somewhere in the vicinity of the sun's equatorial plane. Above this "current sheet" the magnetic field is outward (inward) and its sign reverses below the sheet. The amplitude of the waves is solar cycle dependent. Each pole of the sun maintains its polarity from one solar cycle maximum to the next and changes its polarity each maximum. As the sun rotates the current sheet crosses the Earth producing the sector structure.

It is very important to determine the position of the current sheet on the source surface because this sheet turns out to be an important organizer for many solar wind properties. The sheet position at a few solar radii is now being calculated by Hoeksema (Fig. 6) for each solar rotation using data from the solar observatory at Stanford and potential theory for implying the source surface field from the coronal fields. The positions of current sheets determined by Hoeksema et al., (1983) agree well with those derived from coronagraph observation. Both methods assume that the current sheet is fairly stable on time scales of one solar rotation. They permit predictions of sector boundary crossings to be estimated correctly in a rather gross sense. That is sectors of a few days duration are sometimes missed and sector boundary crossings may be a day or two off. In addition, of course, magnetic fields due to transient events and waves are not predicted. Fig 6 shows the rotation by rotation evolution of the current sheet during the 1979-1980 solar maximum. Note that it is clear that the polarity of the fields at the poles of the sun reversed but is not clear when that change took place.

The contours of constant radial magnetic field on the entire source surface have been calculated from a potential field theory by Suess et al. (1984). Their results are shown in figure 7 where they are also compared to coronal holes deduced from He 10830. In some cases, notably near $210^{\circ}$ Carrington longitude and $0^{\circ}$ Carrington latitude on all three rotations, the agreement is good whereas at other positions, for example the high (southern) latitude hole at $315^{\circ}$ Carrington longitude on all rotations, there is a disagreement. Suess et al. give their results for a surface at 2.6 solar radii whereas the initial conditions for some interplanetary propagation models such as that of Pizzo must be specified at 0.3 AU or about 64 solar radii (1 AU = 214 $R_S$). There will be some changes in the field configuration between 2.6 $R_S$ and 60 $R_S$ if the solar wind expansion between these heights is substantially greater than radial.

The intense southward magnetic field associated with major transient events is a primary factor in causing the largest magnetic storms. These fields are commonly 50 nT or more in intensity. They can come from either of two sources, the distortion of the field in the ambient solar wind by the high speed transient, or an intense southward field contained within the transient plasma itself. It is not known which of these mechanisms is most important. If the field is contained within the driver its value must be specified at the source surface in order that it be included properly as part of the interplanetary modeling. The specification at the source surface would require some way to predict it from observing parameters of the transient event. Tang et al., (1985) have investigated the relationship of the direction of the field at Earth during flare associated events to the

field at the surface of the sun before the flare took place. They were unable to find a statistically significant relationship.

As described in section 2, average plasma properties near the sun were inferred from Helios observations as a function of velocity (Marsch and Richter, 1984). Suess et al. (1984) use data from 1 AU to estimate the solar wind speed and magnetic field intensity on a surface near the sun. They use a constant velocity approximation in tracing parcels of plasma back to the solar vicinity.

Analysis of solar wind properties at 1 AU as a function of time relative to sector boundary structure show that the solar wind velocity, density, temperature and composition (Borrini et al., 1981) are organized relative to the current sheet. The velocity observations were put on a more modern basis by Newkirk and Fisk (1985) who studied the 18 years of velocity observations as a function of distance from the current sheet. They found (figure 8) a large scatter in the data but there was a minimum in speed of 400 km/sec near the current sheet with a rise to an average of about 600 km/sec between $20^{\circ}$ and $40^{\circ}$ from the sheet and a plateau at 600 km/sec at still higher sheet latitudes. This configuration was solar cycle phase dependent for moderate and low activity. At solar maximum there is no obvious systematic ordering. In order to infer the velocity pattern at the source surface it would be necessary to "undo" the effects of stream interactions between the source surface and 1 AU. It may be that this would result in an even more orderly pattern closer to the sun.

Henning et al. (1985) investigated the effect of the position of the heliospheric current sheet on the geoeffectiveness of flares and found that flares occurring on the same side of the current sheet as the Earth are more geo-effective than flares occurring on the opposite side of the current sheet. They suggested the effect was due to the fact that if an event has to travel through the current sheet in the interplanetary medium it might be weakened because of the high density there. They also investigated the distance of each flare from the current sheet and found flares tended to occur closer to the current sheet than would be expected even after eliminating the effect of the sunspot cycle dependence of the latitude of solar flares.

To predict statistical behavior of the southward interplanetary field the Alfven wave flux from the sun would also need to be known as a function of latitude.

Several models of the behavior of the solar wind or transients in the corona have been developed. The results of a model in which the magnetic field configuration and plasma properties are confined to be consistent with one another is shown in figure 9 from Steinolfson et al. (1982). The initial magnetic field was dipolar. The velocity and magnetic field are functions of the angle. The velocity is lowest and the field is highest in the equatorial plane. Steinolfson et al. (1982) has also modeled loop transients within the corona, assuming the event is a sudden deposition of mass and energy into the corona. Steinolfson and Dryer (1984) bring a

transient disturbance through the critical point for the one dimensional magnetohydrodynamic case. They found that a shock is produced inside the critical point. The case of a transient being accelerated within the corona has not yet been modeled, partly because the acceleration mechanism is still under study.

## Conclusions

This review has been a survey of the current state of knowledge of solar corona/solar wind coupling. We have identified several important problem areas in which work is needed to improve our ability to predict the emission from the solar corona of geoeffective solar wind, that is high velocity solar wind and/or solar wind which will result in the appearance of a southward magnetic field at Earth. An improved ability to predict these events will increase the capability of the Air Force to predict and forecast disturbed geomagnetic activity. These problem areas are listed specifically in the accompanying report entitled Corona-Solar Wind Coupling: Program Plans, which also outlines a 3 and 10 year research program designed to develop an enhanced prediction capability.

## Acknowledgements:

I wish to acknowledge the help of a large number of colleagues who provided preprints and spoke to me about their current work during the preparation of this report. I can only list a few of those people here. I thank especially R. C. Altrock, J. V. Hollweg, A. J. Hundhausen, G. W. Pneuman, V. Pizzo, M. Shea, R. S. Steinolfson, S. T. Suess and W. J. Wagner

## FIGURE CAPTIONS

Figure 1 Sketches showing the contrasts between solar wind structures due to steady flow (as from coronal holes) and structures due to transient flows. The lines indicate the magnetic field directions. The black arows indicate the particle velocity direction. The shaded regions show compmressed solar wind and the material within the transient. Adapted from Hundhausen, 1972.

Figure 2 Solar wind velocity in a model in which the solar wind is accelerated by diamagnetic plasmoids in addition to the usual gas pressure. R is the ratio of the mass flux carried by diamagnetic elements to the total mass flux. From Pneuman, 1983.

Figure 3 A comparison between interplanetary field intensities (top panel)and the magnetic field strength in coronal holes (bottom panel). The top panel (from Slavin and Smith, 1983) shows the inverse log of the annual averages or the field at 1 AU. Note that the field strengths in the bottom panel (from Webb and Davis, 1985) exhibits an increase in 1978-79, as does the interplanetary field. It is not known if these two effects are physically related.

Figure 4 Schematic representation of the coronal transient at several times during the event of Aug 5, 1980 as seen by the High Altitude Observatory's coronagraph on board Solar Maximum Mission. From Illing and Hundhausen, 1985.

Figure 5 The relation between the Comprehensive Flare Index (CFI) and large geomagnetic storms. See text for a definition of CFI. From Hedeman and Dodson-Prince, 1980.

Figure 6 The heliospheric current sheet as derived from solar observatories. Solar Maximum occured during this period. Each panel shows the current sheet as the boundary between inward and outward field regions. The latitude range in each panel is $\pm$ 85°. The period shown covers sunspot maximum. Note that the polar magnetic field changes direction, however the exact time of the reversal cannot be pinpointed. From Hoeksema et al., 1983.

Figure 7 Contours of constant radial magnetic field strnegth on a surface at 2.6 solar radii. Dashed lines indicate field pointing toward the sun. The contours are at 0.25, 3, 6 and 9 micro T. Also shown in hatched closed contours are the locations of coronal holes from He 10830. From Suess et al., 1984.

Figure 8 Plot of 732 daily averages of solar wind velocity during 1973-1977 versus angular distance from the current sheet. Disturbed days have been omitted. Mean values (solid circles) and their standard deviations are plotted for each 10 interval in angle. From Newkirk and Fisk, 1985.

Figure 9 A model of a transient in the corona. In this model the magnetic field and plasma properties are confined to be consisted with one another. The lines indicate the direction of the magnetic field

The arrows point in the direction of the velocity and their length is proportional to the speed. The dashed curve shows the position at which the velocity becomes supersonic and the dashed line is the super Alfvenic positon. The arc between the vertical and horizontal axes at 5 solar radii gives the limit of the model. From Steinolfson et al. 1982.

Fig. 1

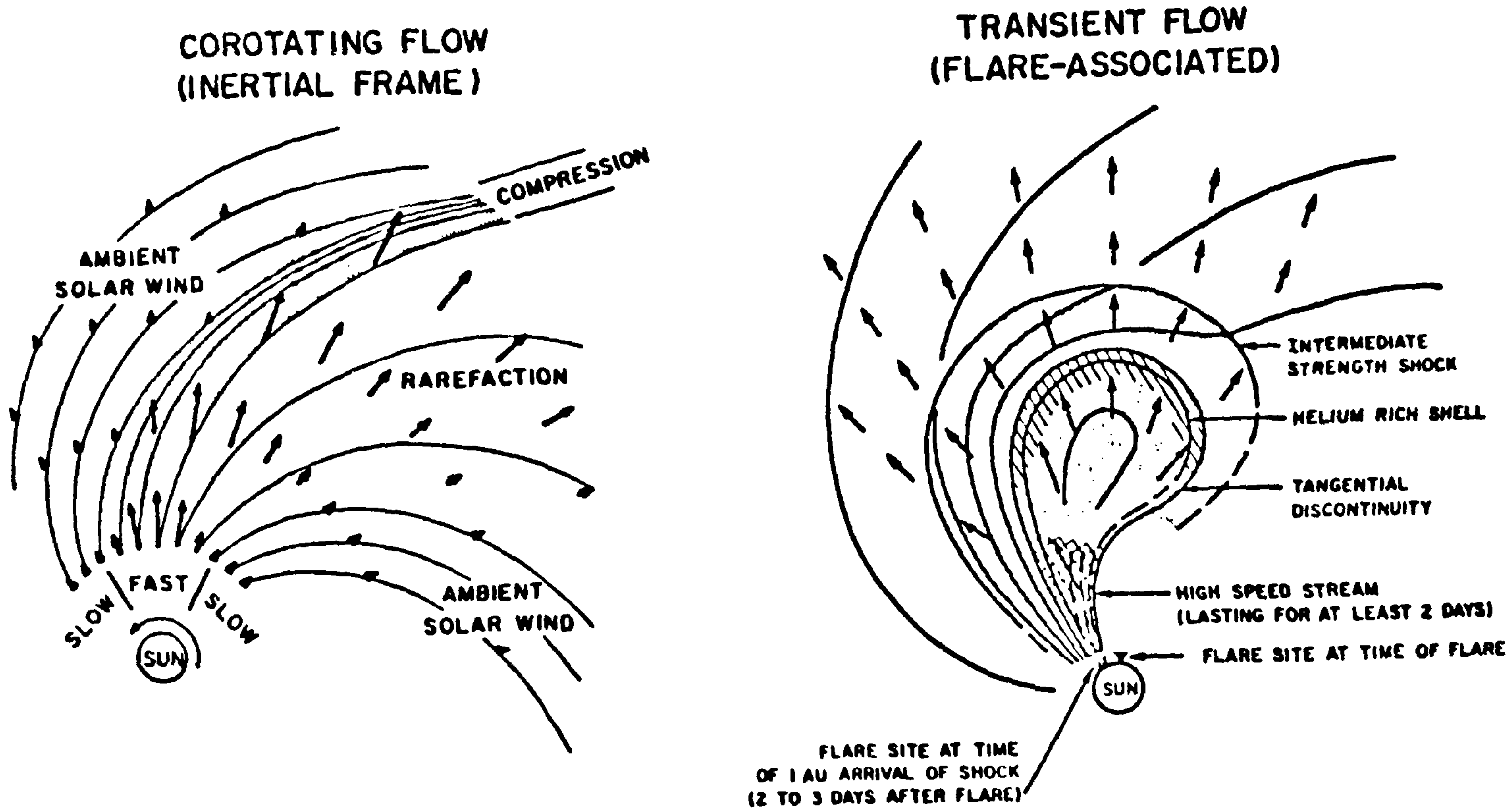
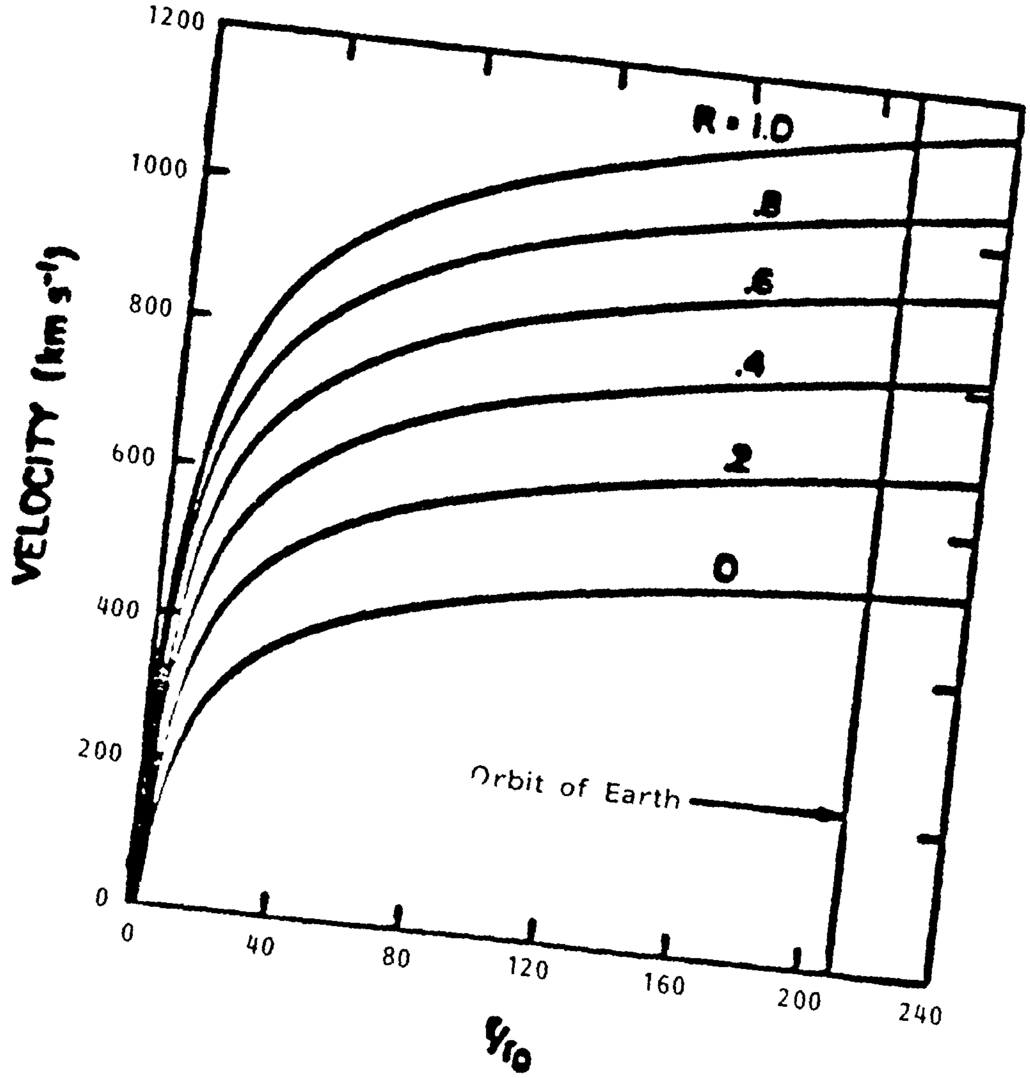
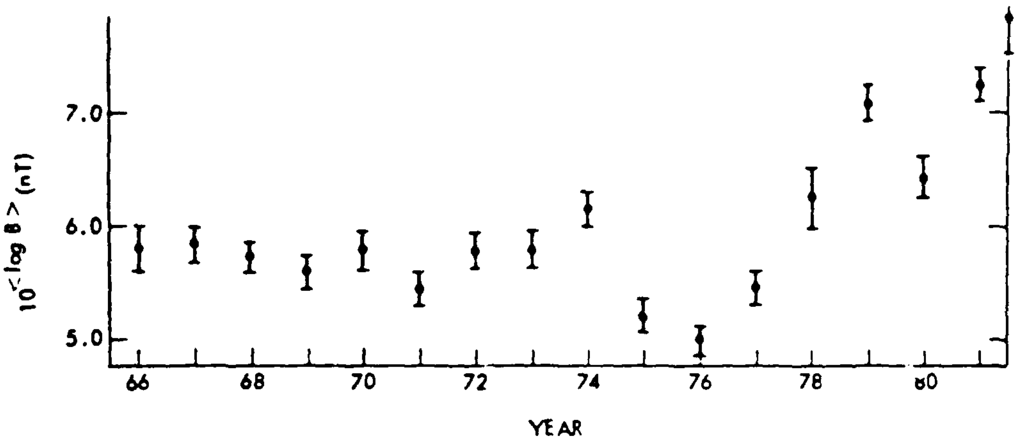

COROTATING FLOW
(INERTIAL FRAME)
AMBIENT
SOLAR WIND
COMPRESSION
RAREFACTION
FAST
SLOW
SLOW
SUN
AMBIENT
SOLAR WIND
TRANSIENT FLOW
(FLARE-ASSOCIATED)
INTERMEDIATE
STRENGTH SHOCK
HELIUM RICH SHELL
TANGENTIAL
DISCONTINUITY
HIGH SPEED STREAM
(LASTING FOR AT LEAST 2 DAYS)
FLARE SITE AT TIME OF FLARE
SUN
FLARE SITE AT TIME
OF 1 AU ARRIVAL OF SHOCK
(2 TO 3 DAYS AFTER FLARE)

Fig. 2



1200
1000
800
600
400
200
0
0
40
80
120
160
200
240
VELOCITY (km s⁻¹)
R = 1.0
.8
.6
.4
.2
0
Orbit of Earth
$q/r_0$

Fig. 3


7.0
6.0
5.0
$10^{<\log B>}$ (nT)
66
68
70
72
74
76
78
80
YEAR

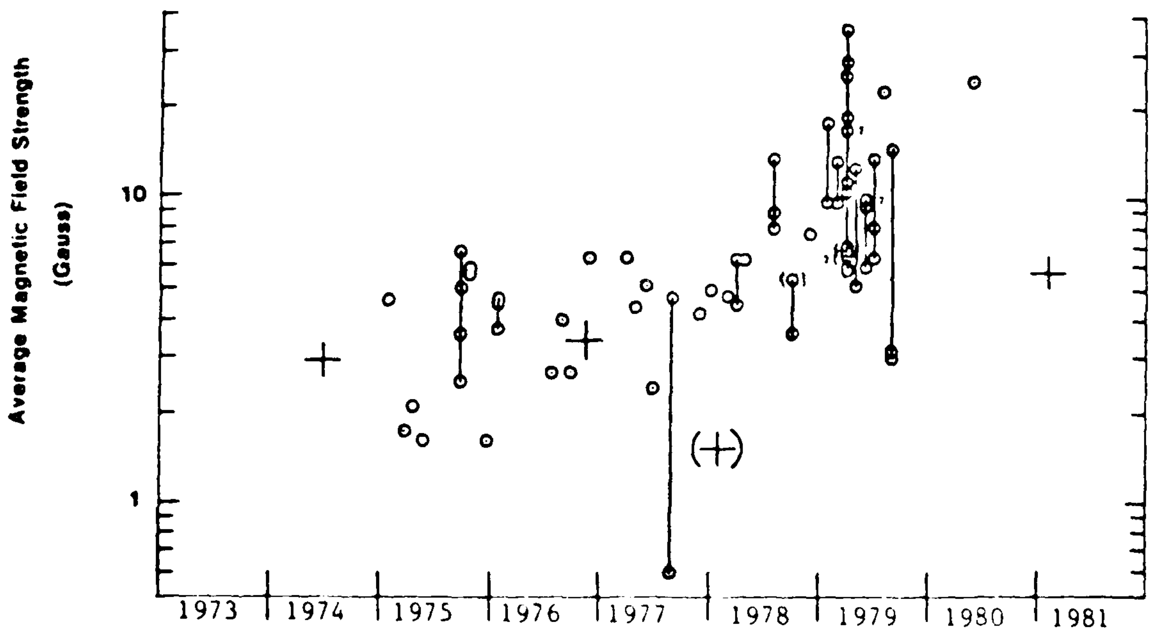

Average Magnetic Field Strength
(Gauss)
10
1
1973
1974
1975
1976
1977
1978
1979
1980
1981

Fig. 4

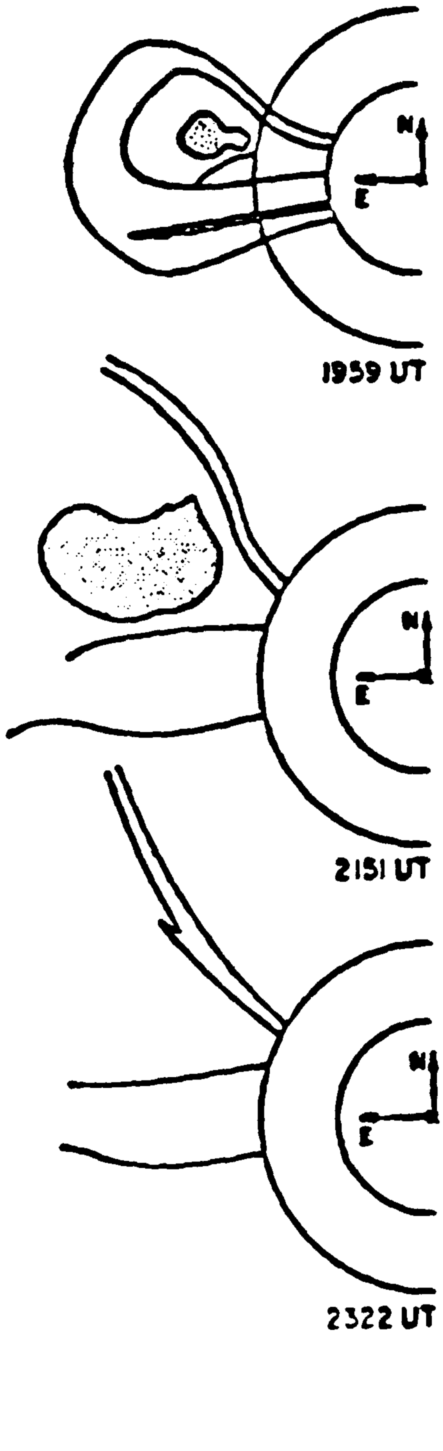
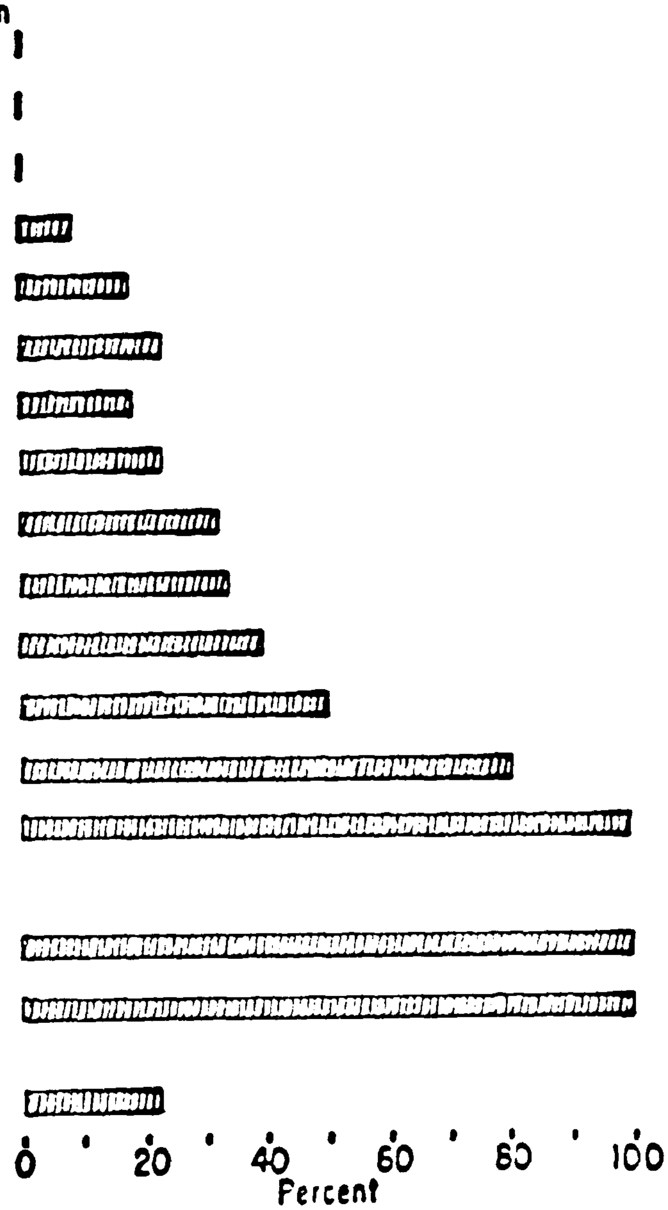


Fig. 5

Number and Percent of "Major" Flares
with Different Values of the Comprehensive Flare Index (CFI),
Associated with Geomagnetic Storms with Maximum 3-Hourly Kp $\geq 5$, 1965-1968.

| CFI | Number of "Major" Flares (1965-1968) Total | Without Storm | Storm Associated | Percent with Storm |
|---|---|---|---|---|
| 1 | 13 | 13 | 0 | 0 |
| 2 | 16 | 16 | 0 | 0 |
| 3 | 27 | 27 | 0 | 0 |
| 4 | 33 | 30 | 3 | 9 |
| 5 | 31 | 25 | 6 | 18 |
| 6 | 35 | 27 | 8 | 23 |
| 7 | 21 | 17 | 4 | 19 |
| 8 | 26 | 20 | 6 | 23 |
| 9 | 28 | 19 | 9 | 32 |
| 10 | 12 | 8 | 4 | 33 |
| 11 | 5 | 3 | 2 | 40 |
| 12 | 10 | 5 | 5 | 50 |
| 13 | 5 | 1 | 4 | 80 |
| 14 | 4 | 0 | 4 | 100 |
| 15 | - | - | - | - |
| 16 | 2 | 0 | 2 | 100 |
| 17 | 1 | 0 | 1 | 100 |
| Total | 269 | 211 | +58 | 22 |




+ Includes the "ambiguous" as well as the uniquely storm-associated flares.

Fig. 6

HELIOSPHERIC CURRENT SHEET STRUCTURE

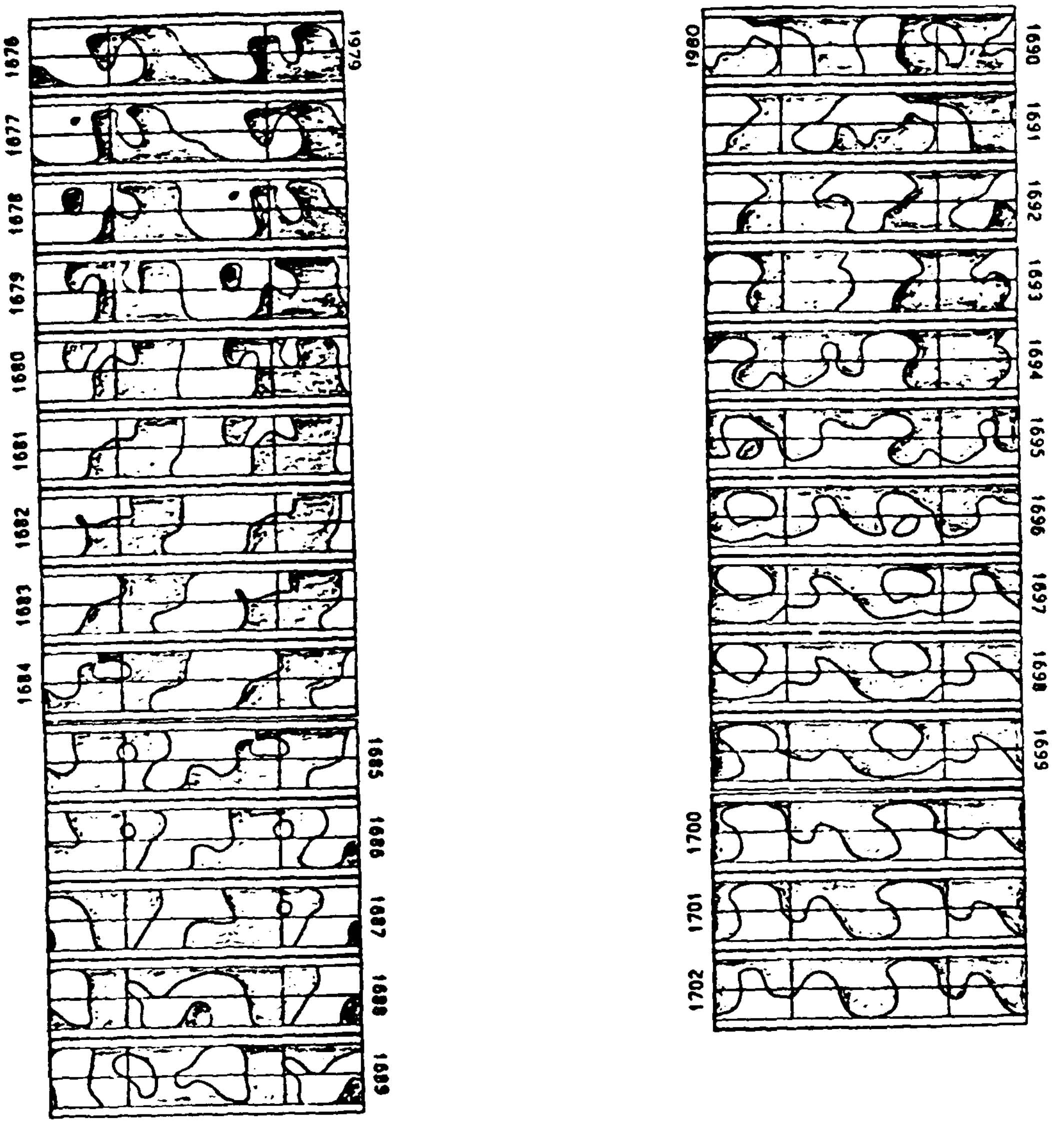
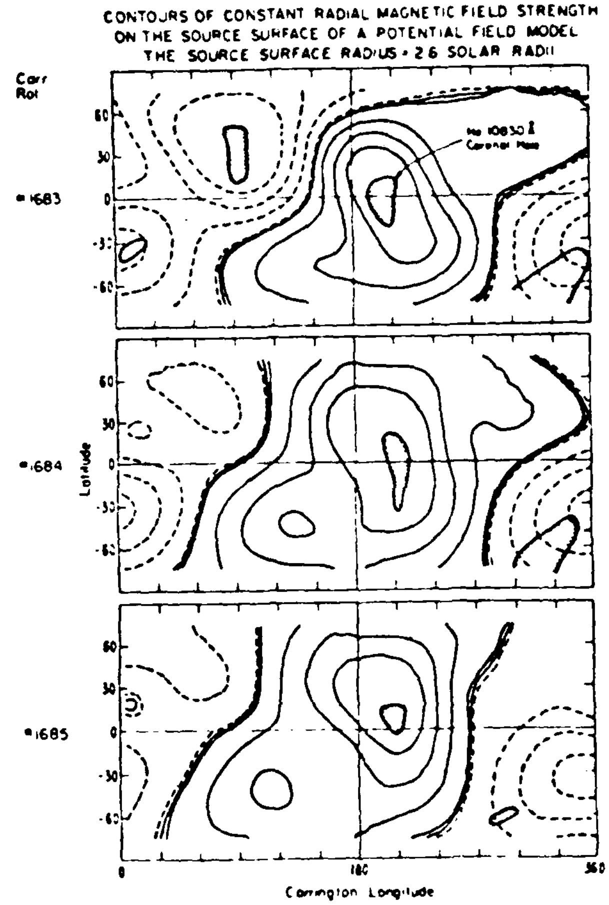


Fig. 7



CONTOURS OF CONSTANT RADIAL MAGNETIC FIELD STRENGTH
ON THE SOURCE SURFACE OF A POTENTIAL FIELD MODEL
THE SOURCE SURFACE RADIUS = 2.6 SOLAR RADII
Carr Rot
#1683
#1684
#1685
Latitude
60
30
0
-30
-60
He 10830 Å Coronal Hole
0
180
360
Carrington Longitude

Fig. 8

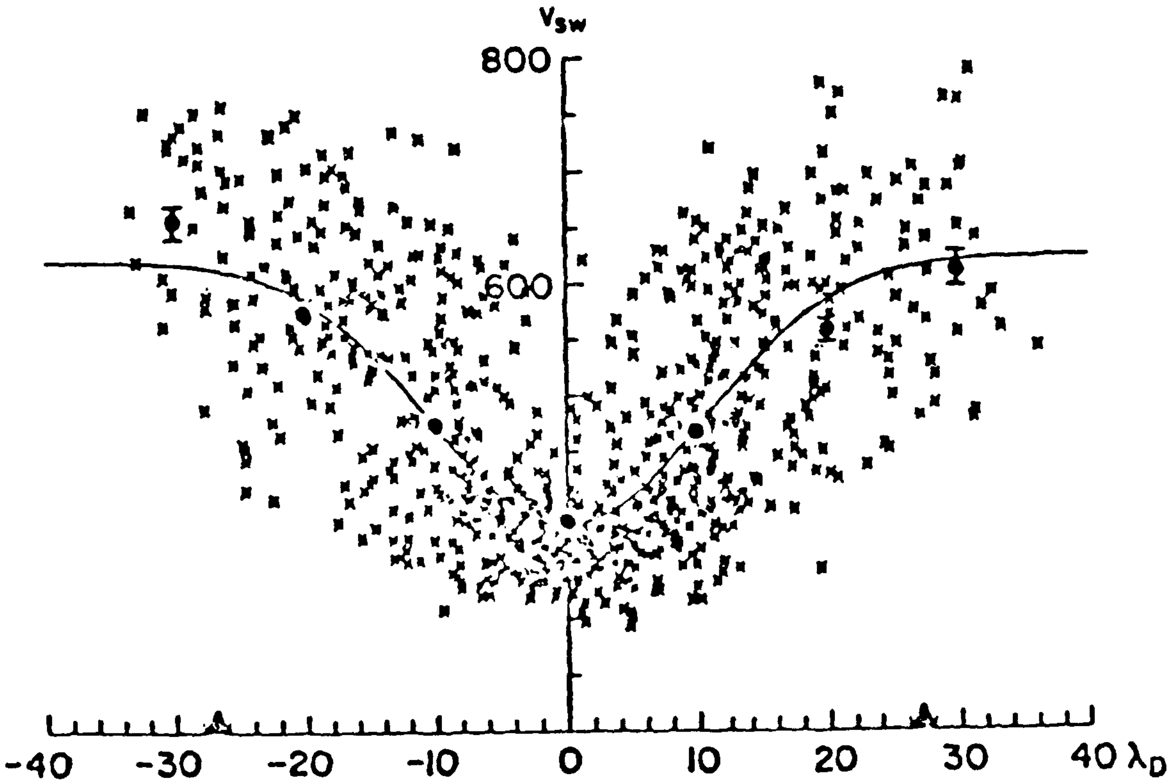


Fig. 9

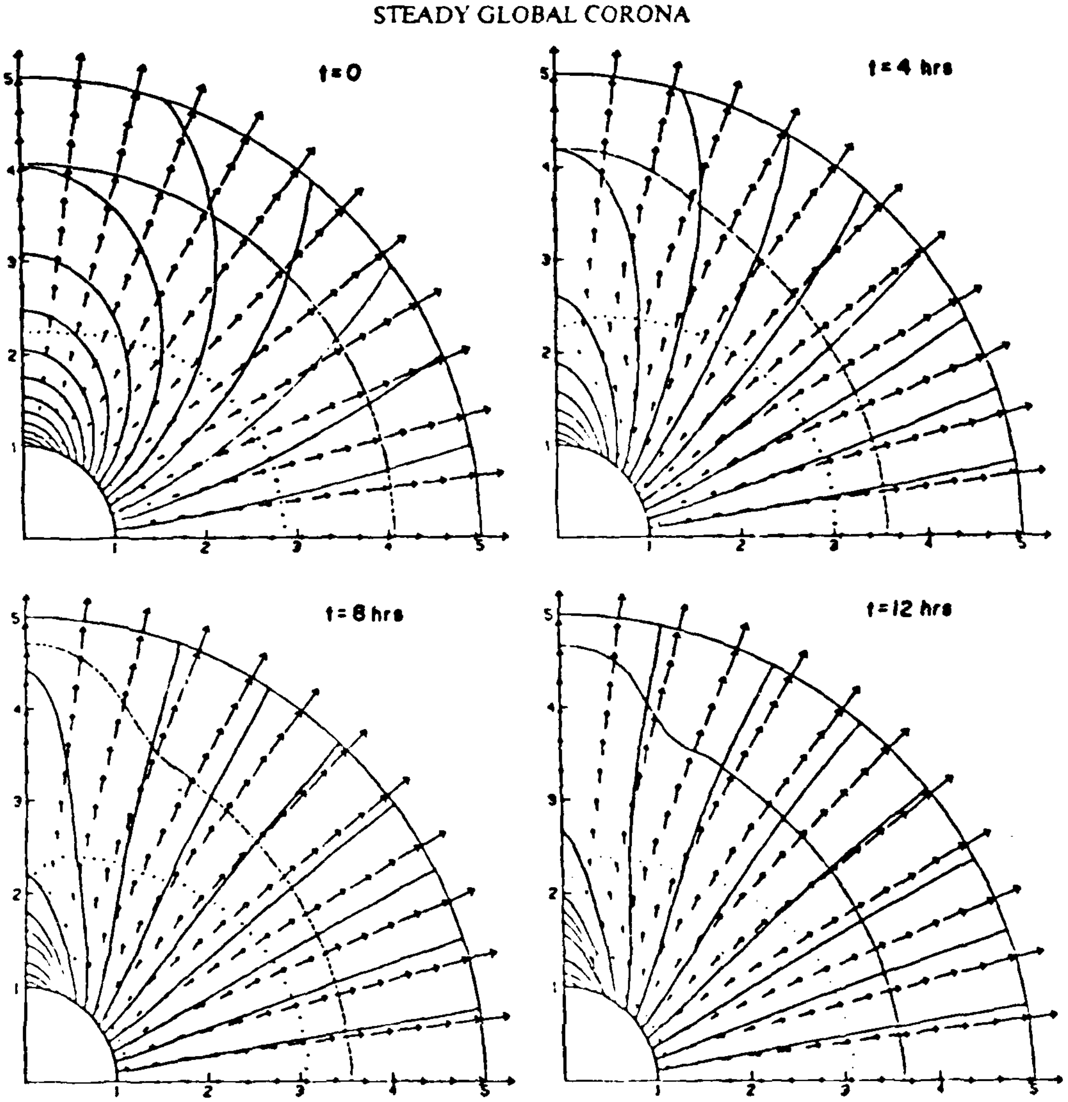


TABLE 1

Observations of Coronal Holes

| Methods | Instrument | Distance Range | Perspective | Ground or Space | Dates | Comment |
|---|---|---|---|---|---|---|
| Soft X ray and XUV | Skylab | Lower corona | Against disk | Space | 1973 for 6 months | The only continuous high quality data set. |
| | Rockets Flights | " " | " " | Space | at approx 18 month intervals. | a high quality glimpse |
| Coronameters | HAO ground based | ~ 1.5 $R_S$ | Holes derived from data in plane of sky. | Ground | Mark 1 1965-67 1969-78 Mark 2 1979 - | holes must be stable on time scales comparable to 27 day solar rotation. |
| Various Mg. Fe and He lines | OSO-6, OSO-7 | Lower corona and chromosphere | Against disk | Space | 1960's and early 1970 | Data from many sources put together by Broussard (1978). |
| He 10830 | Kitt Peak | Chromosphere | Against disk | Ground | 1974 to present | Difficult, also doesn't show sharp outline of holes. |
| Fe XIV 5303 | Sac. Peak | Coronal | Data in plane of the sky. | Ground | 1976 to present | Method still under development. |

TABLE 2

Observations of Transients

| Methods | Instrument | Distance Range | Perspective | Ground or Space | Dates | Comment |
|---|---|---|---|---|---|---|
| White light coronameter | Skylab HAO | | Projection against sky | Space | 1973 - 1974 | |
| | Solar Maximum Mission, HAO (also polarimeter) | 1.8 to 5 $R_S$ | Projection against sky | Space | 1980, 1984 to present | Data not differenced during analysis. |
| | Mauna Loa Observatory | Mark 2 1.2 to 2 $R_S$ | Projection against sky | Ground | Mark 1 1965-67 1969-78 Mark 2 1979 - | |
| | Solwind NRL | 2 or 3 to 10 RS | " " | Space | 1979 - 1985 | Data differenced during analysis |
| Zodiacal light | HELIOS | 0.5 AU | Nearest solar approach of line of sight | Space | | New Method |
| NASA Deep Space Network | | In Space | Variable | Ground | | New Method |
| Fe XIV | | | Against Sky | | | Experimental Stage |

CORONA - SOLAR WIND COUPLING
REFERENCE LIST *

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APPENDIX A

# REPORT ON INTERPLANETARY PROPAGATION OF SOLAR WIND DISTURBANCES *

J. FEYNMAN

## INTRODUCTION

The purpose of this brief review of interplanetary propagation was to set the stage for a discussion of problems the solution of which would aid in developing an ability to predict conditions within the magnetosphere. The way these predictions are now made is to predict the level of geomagnetic activity from space observations and of geomagnetic activity. It will probably be possible in the future to predict the probability of a particular condition of interest (for example the particle fluxes at a particular position in the magnetosphere) directly from solar wind observations, without going through the level of geomagnetic activity. However, that is not currently possible since little work has been done using that approach.

A list of the major solar wind parameters that are changed during propagation is given in viewgraph 1. In order to predict geomagnetic activity we must first identify the solar wind parameters we will need to know. Although a great many studies have been done on determining the best function of interplanetary parameters to use to describe the coupling between the solar wind and the magnetosphere there is no general agreement on the results. However, there is agreement on which parameters are most important. They are the velocity and the southward component of the interplanetary field or alternatively the magnitude and direction of the field. We will call this field the geo-effective IMF and readers can make their favorite choice. The density of the interplanetary medium is also useful for predicting geomagnetics. This review will concentrate on those parameters and how they are changed during the propagation between the sun and the earth.

* This material was originally written as an informal report for the Strategic Defense Initiative (SDI) Workshop on Solar Terrestrial Relations held at the Air Force Geophysics Lab. Bedford, MA June 24, 25, 1985. Although I have included suggestions made at the workshop these remarks are mine and have not been put to the workshop for a consensus.

Two types of disturbances that cause geomagnetic storms are distinguished in the literature; fast streams from coronal holes and disturbances related to transient emissions of solar wind. They are shown schematicaly in figure 1 of Corona-Solar Wind Coupling: Review. In actuality it is probable that there is no clear dichotomy between these types of disturances.

In section 1 below I review the stream work, and in section 2 the transients and in 3 interactions among transients and streams. The outstanding problems are gathered in section 4.

## SECTION 1: STREAMS

Streams have been studied both empirically and through modeling. Viewgraph 2 shows a schematic of the observations at Earth. There is a high density peak ocurring before the velocity peak.

Streams have been modeled extensively. The scheme most often used is to begin the calculation on a surface (called the source surface) which is a few tenths of a AU from the sun but in the region where the wind has become supersonic. The problem of determining what the initial values of solar wind parameters on the source surface is an active region of research at the present. The position of the interplanetary neutral sheet at the source surface seems to be reasonably well predicted from coronal observations. Current work is showing that values of velocity, density, temperature and magnetic field intensity are apparently ordered by distance from the neutral sheet and this is currently being worked on by several groups.

Stream flow modeling in the interplanetary region has been done at several levels of approximation. The problem is of course, a three dimensional (3D) magnetohydrodynamic (MHD) one. Tests have been made to study the effects of approximations. Viewgraph 3 compares a 2D calculation with and without magnetic fields. There is a large magnetic field effect on the particle density and some effect on the steepening of the velocity structure and on the time of arrival of the disturbance at Earth. Viewgraph 4 compares 1, 2, and 3D MHD calculations. There are major differences between 1D ad 2D but the differences between 2 and 3D calculations are relatively small. It appeared to be the sense of the workshop* that the differences in computer requirements between 2 and 3D calculations was so large and the differences between the results so small that a 3D operational predictive model would not be worth the expense.

The models that we have, although sophisticated, are not completely satisfactory. The most severe test to which they have been put is a study in which the initial conditions were given by the solar wind observations at 0.3 AU from HELIOS. The model calculations showed a shock in the wind at Earth, but no shock was observed. Shocks in the real wind are very unusual with streams but appear in the calculations quite readily. The reason for this is unknown although it has been speculated that it may be caused by the fact that the models assume that the stream parameters are completely time independant whereas the wind is probably changing somewhat.

The geo-effective magnetic field is not properly predicted by these models. A steady solar wind would not carry a field in the meridional direction because of the symmetries of the problem. Some meridional (i. e. Bz) field might be induced by the stream interactions if the streams were narrow in latitude. However observations show that the southward field at Earth has a sharp strong peak near the density peak of the streams which is not predicted by the flow models. It has been speculated that this peak is due to the waves and turbulence induced by stream-stream interactions but this has not been established. The waves in this region of the stream have been described as a combination of Alfven waves and magnetosonic waves. Magnetosonic waves are not as common in other regions of the streams. Studies have also been made of the Alfven waves which appear in other regions of the streams. The waves observed at HELIOS (~0.3 AU) were compared to those at earth and the differences in the spectrum could be explained by current theories of Alfven wave propagation. Recently the concepts of turbulence have been invoked to described these IMF variations.

SECTION 2: TRANSIENT DISTURBANCES

The second type of solar wind disturbance is the transient disturbance, a schematic of which is shown in figure 1 of Corona-Solar Wind Coupling: Review. High speed solar wind is emitted from the sun, often associated with a solar flare or other transient phenomena. The transients that cause major magnetic storms are particularly likely to occur at the time of major flares and this is the type of disturbance described here and shown in the viewgraph. In this case the high speed wind is supersonic with respect to the ambient pre-disturbance wind and a shock forms in front of geomagnetic storms, is usually of intermediate strength when observed near Earth. Behind the shock there is compressed ambient solar wind. This is followed by the discontinuity between the ambient wind and the high speed transient wind (the driver). Very large magnetic fields (often southward) are typically observed at earth during distrubances of this kind. These intense magnetic fields are very important in producing geomagnetic activity because, combined with the high velocities of the wind, they cause the most intense storms. However, it is not known to what extent these high intensity fields are due to the distortion of the fields in the ambient wind and to what extent they occur in the driver. As in the case of streams, the geo-effective IMF observed at Earth is at least partially due to plasma waves and turbulence and the occurance of these waves and their contribution to the field at Earth both behind the shock and in the driver are plasma physical effects and not predicted by MHD models. They require further empirical and theoretical study.

There are still some basic empirical questions concerning the propagation of transients in the solar wind. One of the most important of these is the question of the longitudinal extent of the disturbance. Several studies have shown that the longitudinal extent is sometimes very wide (approximated by a circle of radius 0.6 AU and centered on a point at 0.4 AU). The question that remains is whether or not the disturbance front is always very wide and if not, what is the frequency distribution of shock from widths? This is, of course, very important for prediction purposes.

High speed transient wind near the sun has been studied by several groups. The major emissions of solar wind described above are an energetic subclass of a

much more frequent phenomena, "coronal transients". Coronal transients in general occur at the rate of one or two a day and their velocities range from very low values to the high values that cause the structures shown in figure 1 of Corona-Solar Wind Coupling: Review. Although there is as yet no general agreement on the physics of coronal transient acceleration some modelling has been done of the transient as it passes through the corona. These models will not be reviewed here because they are a problem of sources of the wind and not propagation. However, there is a problem of special interest to interplanetary propagation. Interplanetary propagation models begin calculations at a source surface far enough away from the sun so that the ambient solar wind and the transient wind are both already supersonic. The models of the coronal propagation of transients have not been taken through the critical points out to the source surface. The modellers at the conference felt that this problem did not present any basic difficulties and could be done quite readily.

Interplanetary propagation of transient disturbances has also been studied for many years. Viewgraph 6 shows a 2D MHD model of a transient disturbance propagating into a homogeneous ambient solar wind as the disturbance front travels from 0.1 AU to 1 AU. The formation of shocks and a rarefaction are seen.

SECTION 3: TRANSIENTS PROPAGATING INTO INHOMOGENEOUS SOLAR WIND

It is often quite difficult to compare the results of model calculations to observations because in the actual solar wind the disturbance does not propagate into a homogeneous ambient wind and the structures within the ambient can have a profound effect on the observations. Viewgraph 6 shows some results of a model calculation in which a transient was allowed to propagate into an ambient solar wind stream (the stream in viewgraph 2.) The viewgraph shows the disturbance as it would be observed at Earth at different positions in the ambient stream and illustrates the importance of the interactions among disturbances to predicting the appearance of events at Earth.

The problem of modeling the propation of solar wind stream or transient disturbances in a 3D MHD model taking into account all ambient solar wind time dependences and latitudinal and longitudinal inhomogentieties in space is a forbidding project. Various simplifications have been made. The 2 and 3D MHD models already discussed simplify the latitudinal, longitudinal and the tme dependences of the ambient wind but retain the physics of the flow equations. A second approach which has also been attempted is to retain some of the complexities within the ambient wind but to simplify and approximate the treatment of the flow. This approach is especially useful in trying to get a picture of the effects of the underlying ambient wind in predicting what observations can be expected at Earth.

SECTION 4: OUTSTANDING PROBLEMS

INITIAL CONDITIONS: Source Surface

The parameters that must be specified on the source surface for model calculations include, velocity, density, temperature, magnetic field and Alfven flux. More work needs to be done to be able to predict solar wind parameters on the source surface as a function of time from solar observations. An important

problem under this heading is the determination of the magnitude and direction of the magnetic field in the transient driver wind at the source surface. (This entire area is an active one at present but has not been reviewed here because it is a question of sun-solar wind coupling rather than interplanetary propagation.)

## Observational Questions

Viewgraph 7 shows a list of outstanding questions that remain to be studied in order to be able to predict geomagnetic activity.

- The longitudinal and latitudinal extent of structures associated with geo-effective transients at 1 AU has not yet been satisfactorily determined. For example, it is generally agreed that many shocks have a broad front, covering over 60° in longitude. What percentage of disturbance fronts are of large longitudinal extent. If some are relatively narrow, can we predict which ones will be narrow? What is the typical longitudinal extent of he driver?

- The latitudinal structure of streams is not yet well described. This is an area of active research at present, involving several groups.

- The contribution of waves and turbulence to the geo-effective field should be evaluated. The intensity of the southward field component of the IMF in streams can not be predicted from current propagation studies alone because it is very likely due to waves and turbulence generated during the propagation through interplanetary space. Both Alfven waves and magnetosonic waves contribute (the language of turbulence may be more appropriate.)

- Carry out those studies of waves and turbulence that will be required to incorporate this phenomena in propagation models. At present, these phenomena are omitted from propagation model work but, because of their importance in producing the geo-effective IMF, they must be included in some way if we are to produce a propagation model that predicts geomagnetic activity.

- Determine the source of the large geo-effective fields observed at the Earth in transient disturbances. Are they due to a distortion of the pre-existing fields in the ambient plasma or are they due to the field within the driver wind or both? Since these geo-effective fields cause the largest geomagnetic storms and the most hazardous magnetospheric conditions, this question must be resolved before a propagation model can be used as a prediction tool.

## Modeling and Theory

Viewgraph 8 lists advances required in modeling and theory for the development of an accurate, cost effective prediction tool. Work is currently in progress in all of the areas listed.

- A good deal of work is still required before the initial conditions on the source surface can be adaquately described. Some problems in this area have been mentioned briefly but it has not been reviewed here since it is a corona-solar wind coupling problem and this brief review deals with interplanetary propagation.

- Validation and verification of propagation models should be continued. For example, the most physically comprehensive models that we now have (3D MHD) predict shocks forming at less than 1 AU for realistic input parameters at 0.3 AU. This failure of the models is not understood and until it is we can not be sure that we understand the physics of the problem correctly.

- Development, validation and verification of disturbance interaction models should be continued. Understanding interactions among disturbances (stream-stream stream-transient, and transient-transient) requires more study. We need to know how important to the prediction effort we expect the results to be for realistic parameters of the solar wind. These models should probably be of two kinds, one that simplifies the geometry of the problem but retains the physics of flow and the other that simplifies the physics of the flow but maintains the complexity of the geometry.

- Theoretical studies of interplanetary production and attenuation of geo-effective waves and turbulence are required before this important cause of geomagnetic disturbances can be included in propagation models.

- Once understood, waves and turbulence must be incorporated in some way into the prediction propagation models. The first step in this direction may be little more than empirical, but, more sophistiated models can be expected to be developed as the Air Force prediction needs require.

- Simplification of the propagation models developed by the studies outlined above will be required in order to produce a cost effective reliable prediction tool. Once the physical phenomena have been understood and modeled, approximations can be made to produce a working model that adequately reproduce the behavior of the geo-effective parameters at 1 AU.

Viewgraphs

1. Solar wind parameters changed during interplanetary propagation between a source surface (near the sun) and the earth.

2. Schematic of observations of streams at earth. The abscissa gives the time as degrees of solar rotation. Thirty degrees of rotation corresponds to about 50 hours.

3. Comparison of 2 dimensional (D), hydromagnetic (HD) and 2D magnetohydrodynamic (MHD) model results. (from Pizzo, V.J. Interplanetary shocks on a large scale - A retrospective on the last decades theoretical efforts, to appear in proceedings of the Chapman Conference on Collisionless Shock Waves in the Helosphere, Napa Valley, CA FeB 20-24, 1984.)

4. Comparison of 1, 2, and 3D MHD model results (Pizzo, ibid.)

5. A 2D, MHD model of a transient in the solar wind, showing contour maps of log n (n = density). (from D'Uston, C., M. Dryer, S.M. Han and S.T. Wu. Spatial Structure of flare associated perturbations in the solar wind simulated by a two-dimensional numerical MHS model. J. Geophys. Res 86, 525, 1981.)

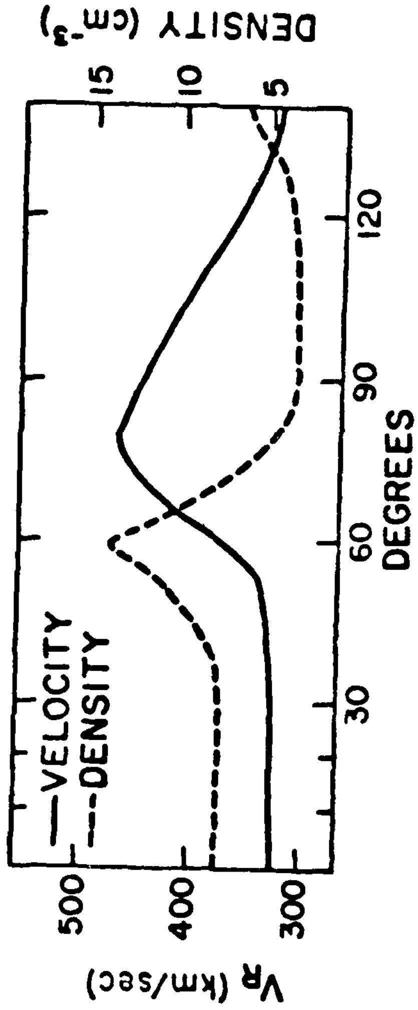
6. A 3D, HD model of a transient propagating into an ambient solar wind containing streams. The top figure gives the density and velocity of the ambient stream (as in view graph 3) and shows the 8 positions of the undisturbed stream at which observations are assumed to be made in the modeling effort. The numbers at the top of the upper graph show the disturbance transit time in hours for the disturbance as observed at each position. The density and velocity changes predicted by the model for each of these positions are shown in the lower panel. (From Hirshberg, J., Y. Nakagawa and R.E. Wellck, Propagation of sudden disturbances through a non-homogeneous solar wind, J. Geophys. Res 79, 3726, 1974).

7. Outstanding problems in producing an accurate, cost effective prediction tool that require analysis of existing observations for solution.

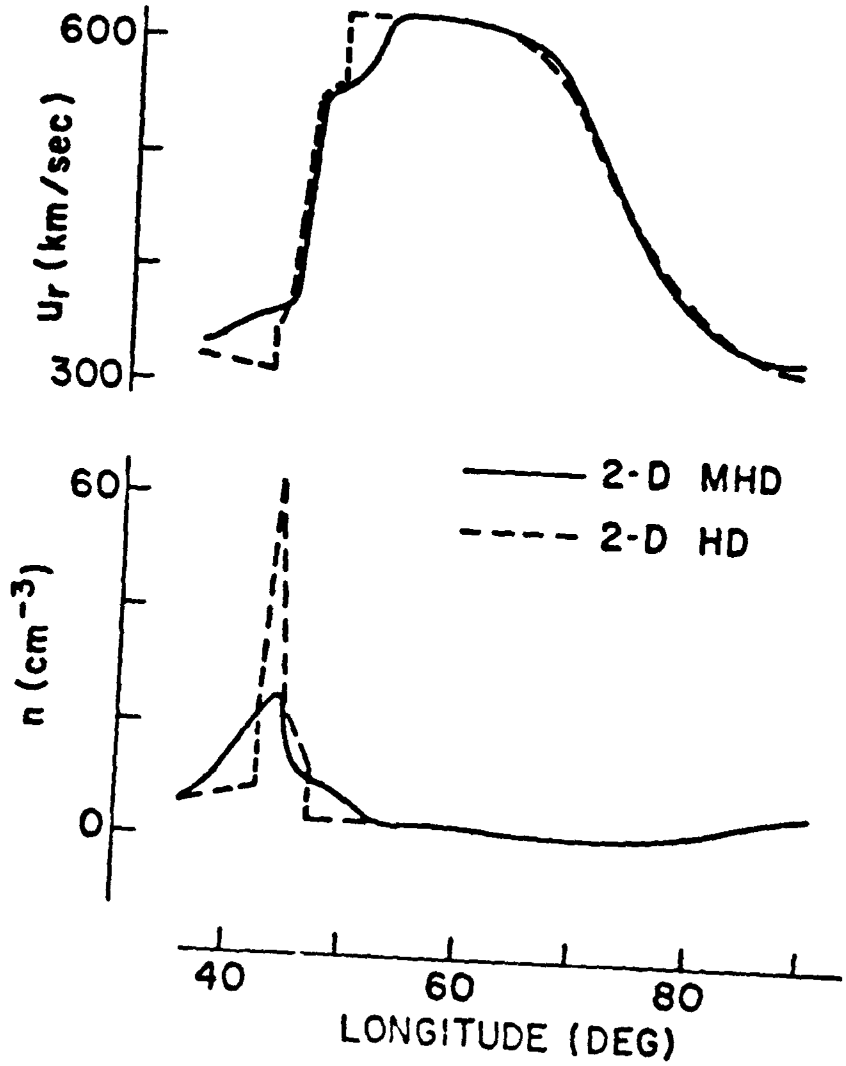
8. Outstanding problems in producing an accurate, cost effective prediction tool that require modeling and/or theoretical efforts for solution.

Parameters Changed During Propagation

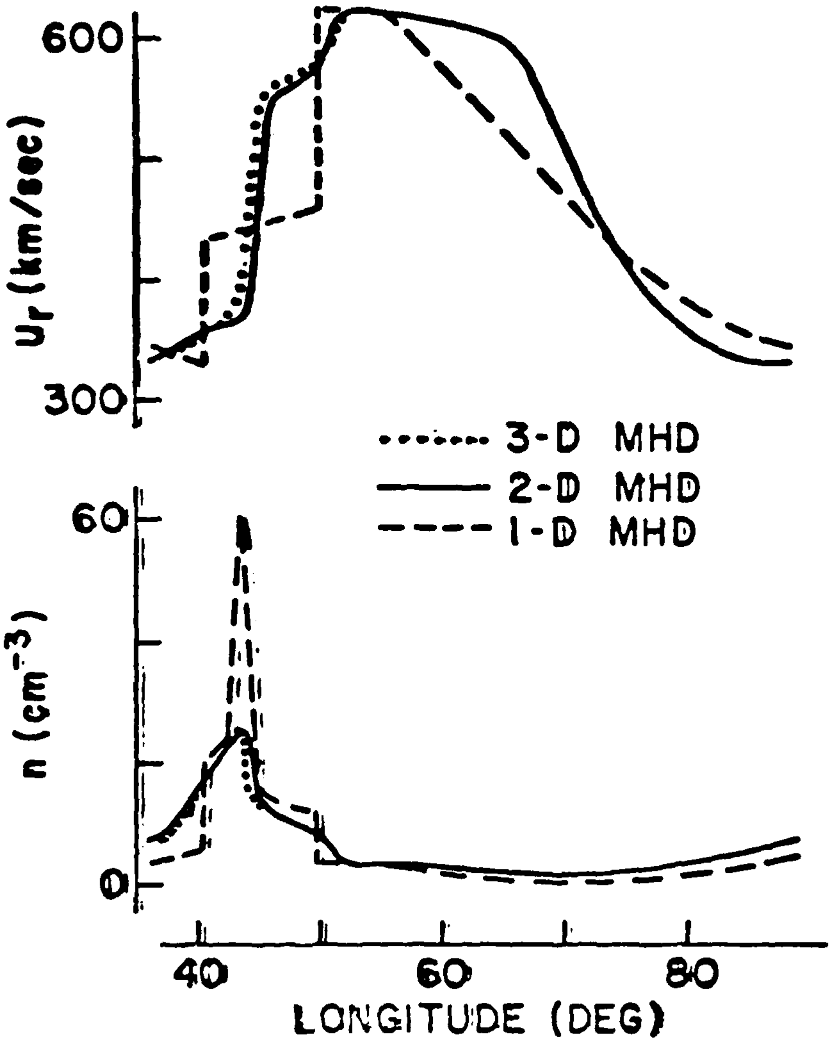
- Magnetic Field, Magnitude and Direction.
- Wave and Turbulence Content.
- Particle Velocity, Temperature, Density and Composition (?)



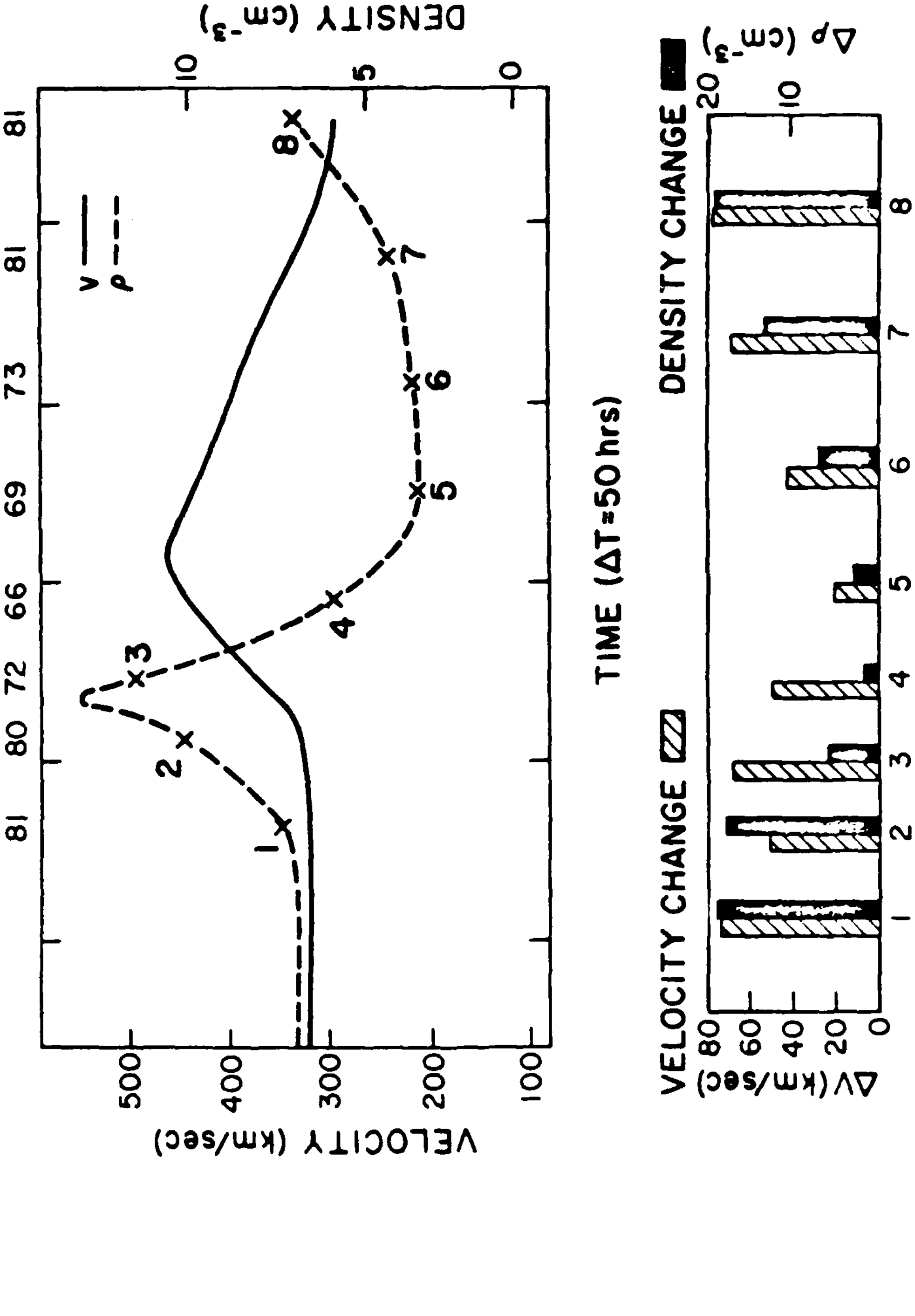
VELOCITY
DENSITY
DEGREES
30
60
90
120
$V_R$ (km/sec)
500
400
300
DENSITY ($cm^{-3}$)
15
10
5



600
300
$U_r$ (km/sec)
60
0
n ($cm^{-3}$)
2-D MHD
2-D HD
40
60
80
LONGITUDE (DEG)



600
300
$U_r$ (km/sec)
3-D MHD
2-D MHD
1-D MHD
60
0
n ($cm^{-3}$)
40
60
80
LONGITUDE (DEG)



VELOCITY (km/sec)
DENSITY (cm⁻³)
TIME (ΔT=50 hrs)
v
ρ
81
80
72
66
69
73
81
81
VELOCITY CHANGE
DENSITY CHANGE
ΔV (km/sec)
Δρ (cm⁻³)

## OUTSTANDING PROBLEMS: INTERPLANETARY PROPAGATION
## OBSERVATIONAL QUESTIONS

- DETERMINE THE LONGITUDINAL AND LATITUDINAL EXTENT OF STRUCTURES ASSOCIATED WITH GEO-EFFECTIVE TRANSIENTS AT 1A.U..
- DETERMINE LATITUDINAL STRUCTURE OF STREAMS .
- EVALUATE THE CONTRIBUTION OF WAVES AND TURBULENCE TO THE GEO-EFFECTIVE FIELD.
- CARRY OUT STUDIES OF WAVE AND TURBULENCE REQUIRED TO INCORPORATE THIS PHENOMENA IN PROPAGATION MODELS.
- DETERMINE THE SOURCE OF LARGE GEO-EFFECTIVE FIELDS IN TRANSIENT DISTURBANCES.

## OUTSTANDING PROBLEMS: INTERPLANETARY PROPAGATION MODELING AND THEORY

- SPECIFICATION OF INITIAL CONDITIONS ON SOURCE SURFACE (CORONA-SOLAR WIND COUPLING PROBLEM).
- CONTINUED VALIDATION AND VERIFICATION OF EXISTING PROPAGATION MODELS.
- CONTINUED DEVELOPMENT, VALIDATION AND VERIFICATION OF DISTURBANCE INTERACTION MODELS.
- THEORETICAL STUDIES OF INTERPLANETARY PRODUCTION OF GEO-EFFECTIVE WAVES AND TURBULENCE.
- INCORPORATION OF WAVES AND TURBULENCE INTO PROPAGATION MODELS.
- SIMPLIFICATION OF RESULTANT MODELS TO PRODUCE A COST EFFECTIVE RELIABLE PREDICTION TOOL.

# Corona-Solar Wind Coupling: Program Plans

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## INTRODUCTION

This report contains a brief description of problems that still remain for the development of an enhanced capability of predicting the level of geomagnetic disturbance. The identification of these problems is based on the review of the literature described in the report entitled Corona-Solar Wind Coupling: Review (J. Feynman, Report 1, 1987). Ten and 3 year research plans designed to address these problems are then presented.

In the first section the list of remaining problems is given. This list was drawn up without regard to the difficulties of the problems. Section 2 presents an integrated 10 year plan designed to address these problems. In section 3 five studies have been selected that are particularly important and appear, in the opinion of the author, to be ready for significant progress if funded for about 800 K/yr ($800,000 per year) among them for a period of 3 years. This is essentially a 3 year plan. No attempt has been made to make recommendations in these plans concerning observational programs since that was assumed to be outside the purview of these studies.

## SECTION 1

This section presents a brief listing of the problems that will need attention in the 10 year plan for research. These problems are discussed in detail in the review of corona solar wind coupling. The organization of this section follows that of the review. The reader should also consult the review for the definition of any unfamiliar terms.

### Causes of Southward $B_Z$

The solar wind parameters that are most important in driving geomagnetic activity are the velocity and the north-south component of the magnetic field, $B_Z$. Although we have only empirical methods of predicting velocity, the situation is even worse for $B_Z$. Very little study has gone into the question of the causes of $B_Z$ in the solar wind and even the empirical description of the occurance of $B_Z$ is rudimentary at best. Very significant progress must be made in identifying and understanding the causes of $B_Z$ before we can develop a good prediction capability. This is the most important unexplored subject in the prediction field.

### Solar wind theory

The unsatisfactory state of solar wind theory after so many years of work by so many scientists suggests that no major advances in the ability to predict geo-effective solar wind parameters can be expected on a short time scale from supporting particular theoretical studies. The most promising approaches at this time appear to be in the areas of the development of self consistent approaches and in some studies of acceleration mechanisms

There are several problems in the self consistent area that are currently receiving attention; self consistent treatments of the composition of the solar atmosphere and solar wind, self consistent wave energy deposition studies to produce the chromosphere corona and solar wind simultaneously. In addition, there are studies of self consistent treatments of the coronal material, solar wind and coronal magnetic field that produce large scale coronal structures such as holes and at the same time produce the wind holes emit. These latter studies are the most promising for prediction. Modeling work in this area is being supported at present and should be continued because of its relevance to prediction. These modeling efforts are included in the 10 and 3 year plans as part of each of the non-theoretical categories.

Several new studies of solar wind acceleration mechanisms are underway. The implications of the idea that the solar wind is accelerated by small scale reconnection and magnetic buoyancy are being examined. Mechanisms to produce the observed acceleration of coronal transients passing through the corona are also being studied. Magnetic buoyancy is an interesting contender here as well. The time - table for payoff for these studies is very uncertain although studies of the acceleration of transients have the advantage of being constrained by new observations. This will be an important area to watch.

## Coronal Holes

Observations:

Observations of holes should be upgraded by resuming space based soft X-ray and XUV observations. These are required for monitoring as well as for obtaining detailed data that would aid empirical and modeling studies of hole - solar wind relations. However, no recommendations on observing programs are included in the program plans given here because that was considered to be beyond the scope of these studies.

Empirical Studies:

The relationship between individual stable holes and the properties of the particular solar wind streams that issue from the holes should be investigated. Studies should include (1) questions concerning the relation between magnetic field flux density in the hole and the solar wind field intensity, (2) questions concerning a comparison of the properties of the holes to the solar wind velocity, (3) and questions concerning the source of southward interplanetary field within solar wind accelerated in holes.

The role of holes as sources of fast solar wind streams should be clarified, especially for relatively short lived holes not contiguous with large polar holes. Do all high speed streams come from holes? Do all holes emit high speed streams?

The behavior of stable holes during the current solar cycle should be compared with that of 1973-1974. The holes of 1973 1974 were probably

unusually large and stable since the associated recurrent geomagnetic storms were unusually strong and stable when compared with the experience of the 9 most recent solar cycles. In what ways do the holes in the current cycle differ from the earlier holes? This may be more difficult to study then it appears due to the lack of continuous space based observations.

Short lived holes should be studied in more detail. What is their life history and relation, if any, to coronal transients? How do they contribute to the geo-effective solar wind?

Modeling:

Continued modeling of solar wind from holes should also be encouraged. The relation between a range of conditions within the hole and the resultant solar wind in space should be investigated. The models should be improved as theoretical advances and the results of observational studies permit. The models should also be verified by comparison with particular hole-wind pairs.

## Coronal Transients

Observations:

Observations from space should be continued at least until ground based techniques are reliable and well calibrated and until we are sure we have the data required for an accurate description of transients, including solar cycle effects. Currently only the NCAR-HAO coronameter-polarimeter is making space observations and it is probable that these will be terminated within the year. Again, no recommendations are included in the program plan

since observational programs are considered to be beyond the scope of these studies.

Empirical Studies:

The empirical description of coronal transients, including solar cycle changes, is still being developed by groups at NRL and HAO. This work should be carried to completion.

For geomagnetic prediction it is important to describe and understand the relationship between transients, flares and rising prominences as well as the relation between major and minor ejections.

The role of coronal transients in the geo-effective solar wind should be further studied. Do transients provide a major source of $B_Z$? Since transients occur at all phases of the solar cycle is it possible that they make the major contribution to $B_Z$ throughout the cycle?

Modeling:

Realistic models of the passage of transients through the corona must wait on theoretical understanding of the acceleration mechanisms that cause the transients to continue to be accelerated while they are passing through the corona. For prediction the aim of such modeling should be to determine the values of the parameters needed at the source surface as input to the interplanetary propagation model. These parameters include velocity, density, temperature and vector magnetic field.

## Slow Solar Wind

The slow solar wind is associated with geomagnetic quiet because of its low velocity. It is also generally believed to be characterized by undisturbed magnetic fields with the spiral field configuration expected from steady state solar wind theory. However, I am not aware of studies that specifically address the detailed description of the magnetic field in the slow solar wind directly.

The sources of the slow solar wind have not as yet been securely determined. There is good evidence both empirically and from modeling that it is associated with the neutral sheet. That concept seems to be at variance with the idea that the slow wind is the wind to which the 2 fluid steady-state spherically symmetric theory pertains. Furthermore, is all slow wind associated with the neutral sheet? Do the parameters describing this wind remain constant over the solar cycle and from solar cycle to solar cycle? Further investigation of these questions is needed and a small effort is recommended in the 10 year plan.

## Source Surface for Interplanetary Propagation

Empirical Studies:

Several studies have recently found that the current sheet orders solar and solar wind properties. Studies of this type should be continued, with particular emphasis on the geo-effective parameters at the source surface and the parameters required as input to interplanetary propagation models.

The Alfven wave flux as a function of position on the source surface should be evaluated empirically. Since the change in intensity of the interplanetary waves with distance from the sun can be estimated and the direction of propagation is believed to be known, it should be possible to estimate the Alfven flux required at the source surface to produce the observed levels at earth. The results of these studies could be used as imput to studies of the coronal sources of these waves.

Estimates of $B_Z$ at the source surface should be attempted by using data collected near earth, and from Helios and from observations of the corona. Estimates of Alfven wave fluxes and studies of mass injections will be important inputs to these studies.

Modeling:

Models of solar wind and magnetic fields associated with holes should be carried out from the lower corona to the source surface for a variety of realistic hole geometries and coronal material and field parameters.

Models of coronal mass ejections appearing at the source surface should be developed when enough is known about the acceleration of the transient material to make the models reasonably realistic.

## SECTION 2

A ten year plan at a level of 800 K/yr ($800,000 per year) has been developed to address the problems listed in Section 1. A summary of the

plan is shown in figure 1. The categories 'theory, source surface, slow solar wind, transients and holes' are the same as those used in report 1 and section 1 of this report. A new category, 'supporting solar wind studies' has been added. This category contains work on the solar wind which is needed to support the planned solar wind-corona coupling studies. The plan is given in units of 100 K ($100,000). Again no funding is recommended for new observations because that was believed to be outside the purview of this study.

The details of the 10 year plan are given in figure 2 which shows the funding levels for the activities under each category.

'Supporting solar wind' includes two types of studies. The first type of study that must be carried out addresses the question of how the southward fields observed in the solar wind are produced. Until we have the answer to that question we will not be able to know exactly which coronal processes must be studied most intensely. The results of these solar wind studies may suggest some changes in the distribution of funds between 'hole' research and 'transient' research. It is more likely however that re-adjustments of funding level will be required among the 'activities' within each of the categories. The second type of study carried out under the category of Supporting Solar Wind Studies is interplanetary modeling studies to incorporate the results of other research projects into current interplanetary models. This needs to be an ongoing effort so that the research findings of the entire corona-solar wind coupling program becomes operative as a prediction upgrade as rapidly as possible.

The activities described under the other five categories are derived from Report 1 and the list of problems given in Section 1 of this report. The funding levels were determined by estimating the difficulty of the problem. In addition programs were funded at higher levels at the beginning of the program if the results of the studies are needed as input to other investigations. For example, the empirical description of the acceleration history of coronal transients needs to be completed before modeling or theoretical studies of the phenomena are carried out. Some modeling can be started before the theoretical work is begun but a theortical understanding should be in hand before the modeling is completed. In another example, funding for studies of the slow solar wind is put off until the last few years of the program because the slow wind is not geo-effective and it does not seem likely that the results will be required as input to the modeling effort.

Figure 3 shows the distribution of the funding between studies involving theory and modeling and studies involving the analysis of data and the verification of the models by comparison with observation. During the early years, the program concentrates heavily on the empirical studies required for future modeling. During the first two years some modeling would be supported as part of the efforts in activities such as the 'role of transients in the geo-effective wind' and/or 'sources of $B_Z$' and or 'properties of individual holes vs. properties of the resultant wind streams'. As the answers to some of the most pressing empirical problems are obtained the theoretical and modeling development efforts receive more

funding. At the end of the fourth year the two major efforts receive equal funding as shown in the figures. In addition, as time goes on the emphasis is changed within each effort as can be seen in the detailed plan in figure 2. The 'empirical and model verification' effort begins in a highly 'empirical studies'mode and shifts to a heavier emphasis on model verification in the later years (figure 2). The 'theoretical and model development' effort is heavily tipped to model development throughout the program. This is because the return to the prediction effort from theoretical studies is so uncertain and also because theory is funded at a high level by NASA in the 'centers of excellence' program they instituted a few years ago. The theoretical effort that begins in the fourth year is expected to be focused on those problems that are especially important to prediction.

## SECTION 3

In this section 5 studies are described in some detail. In the opinion of the author, these studies are ripe for research and would maximize the payoff to a prediction effort program for a research effort limited to 3 years only. They are designed to be funded for a total of 800 K/year. In the 10 year plan discussed in Section 2 these studies are also included but they are distributed a little differently in both funding level and the time at which the study should take place. Specifically the slow solar wind studies which are scheduled for late in the 10 year plan are moved into the three year plan at the expense of studies of the ordering of solar wind properties on the source surface. The recommended funding level for each

study is given for both the 3 year and 10 year plans at the end of each study description and in figure 4. The detailed 3 year plan is shown in figure 5.

Study 1, Sources of southward $B_Z$

Theoretically, a steady expanding solar wind will not have a north south component of the interplanetary field ($B_Z$) at Earth. There are however, four different possible sources of $B_Z$ in the solar wind:

(1) waves coming from the sun,(2) waves produced in the wind by interacting streams, (3) a southward field component within coronal transients as they are emitted into the solar wind, (4) a southward field component induced by distortion of the ambient interplanetary field as the coronal transients propagate through space.

We need first to identify which of these 4 mechanisms is most important in causing the geo-effective $B_Z$. This will require studies of already existing solar wind data. "Prediction" from coronal observations will have somewhat different meanings depending which mechanisms are important.

If the most important cause of $B_Z$ is the existance of a southward field within the transient as it is emitted into the solar wind then we require predictions of when and where transients occur, what the field will be within them (perhaps in the probablistic sense) and how the field will be altered by interplanetary propagation. For the case in which the most important cause of $B_Z$ is being induced in the solar wind by distortion of

the ambient solar wind field by a high speed transient, the field within the transient would no longer be required for prediction. However a prediction of the field within the ambient wind would be needed. Note however it is much simpler to estimate the field expected in the ambient wind then that within the transient as it is emitted from the corona. In either case a model for calculating the effects of interplanetary propagation is required for prediction of $B_Z$ at Earth. Several interplanetary propagation models now exist, some of which would need to be modified to be applicable to the prediction problem.

If a southward $B_Z$ is usually due to waves or turbulence in the solar wind the prediction of $B_Z$ would have to be statistical. We need to predict wave spectra and intensities. It is already known that the Alfven wave spectra appear to be Kolmogorov. There are also some studies describing the regions of high speed streams at which Alfven waves are found. More complete studies are required and coronal sources of high Alfven fluxes should be identified. A more generalized turbulence is produced in the interplanetary medium in the region in which two streams interact. In this region a variety of MHD and plasma waves are produced. Again we need to know to what extent these waves result in a geo-effective $B_Z$ and, if they do so, the wave production, spectrum and intensity should be studied.

The funding level recommended for these studies for the 3 year plan is 500 K over 3 years (figure 5) and for the 10 year plan is 600 K during the first 4 years (figure 2).

Study 2

Relation of solar wind properties to the properties of coronal holes.

Since they were first observed in 1973, a large number of studies have been done to identify the coronal holes from which high speed solar wind is emitted. As a result there are now many cases in which coronal holes are identified with specific streams. Empirical studies of the relation between the properties of specific holes and the properties of the resultant specific solar wind streams have become possible. For example in figure 3 of the report on corona-solar wind sources the top panel gives the magnetic field in space whereas the lower panel gives the flux density at the base of the holes. From the figure there appears to be a relation which was not reported in the literature when this survey was made. Such studies should be carried out for a variety of important parameters such as velocity, mass flux and Alfven wave flux and magnetic field intensity.

In conjunction with the these studies, the development of the self-consistent models of hole-solar wind pairs that is already underway at Marshall Space Flight Center should be encouraged. The funding level recommended for these studies for the 3 year plan is 300 K over 3 years (figure 5) and for the 10 year plan is 500 K over the first 5 years (figure 2).

Study 3

Transients

The role of transients in producing geoeffective solar wind needs more study and can be expected to produce improvements in the prediction

capability relatively rapidly. Work has already been done on the problem of establishing criteria for recognizing transients as they appear in the solar wind. Although these criteria are still the subject of debate, enough has been done so that promising candidates for identification as transient solar wind parcels can be identified. These events can then be studied further. For prediction the most important question is the role of transients in producing southward $B_Z$. In contrast to the quasi-steady solar wind the magnetic field within transient solar wind is not expected to have a preferred direction. For this reason relatively large values of $B_Z$ are expected to occur frequently within the transient. Since transients are common at all phases of the solar cycle it is even possible that they make the major contribution to $B_Z$ throughout the cycle.

The level of funding recommended for these studies is a total of 300 K in the 3 year plan or 900 K distributed over the life of the 10 year plan.

Study 4

Sources of the slow solar wind

In predicting geomagnetic activity it is often important to be able to predict quiet conditions. For this we need to study the sources of the slow solar wind. The wind which is emitted from over helmet streamers is apparently slow but is this the only source of slow solar wind? Does all slow solar wind have the same values of the important geoeffective parameters such as velocity, field intensity and mass flux or are these values dependent on the solar cycle for example. These empirical studies

may be somewhat difficult due to the over-riding of the slow wind by the neighboring higher speed wind as the stream propagates through interplanetary space. However, so little is known about the slow wind that considerable progress may be possible.

This is another area in which modeling is currently underway and should be supported.

The funding level recommended for these studies is 100 K for either the 3 year plan or the 10 year plan. In the 10 year plan these studies are carried out during the last 2 years.

Study 5

Studies of the current-sheet ordering of coronal and solar wind properties

This area is an exciting and promising one for prediction studies because the position of the current sheet at coronal heights can already be determined from solar observations. Furthermore many studies are beginning to show that the current sheet, rather than the solar equatorial plane, is the ordering structure of the sun at all periods of the solar cycle, and for a host of different parameters and processes. Thus if we determine empirically how the geo-effective parameters are arranged relative to the neutral sheet the ability to predict these parameters at earth will be much enhanced. These studies promise to have a good payoff in prediction and should be pursued.

The funding level recommended for these studies for the 3 year plan is 400 K (figure 5) and for the 10 year plan 1,000 K over 10 years (figure 2).

CORONA-SOLAR WIND COUPLING

10 YEAR 800 K/yr PLAN

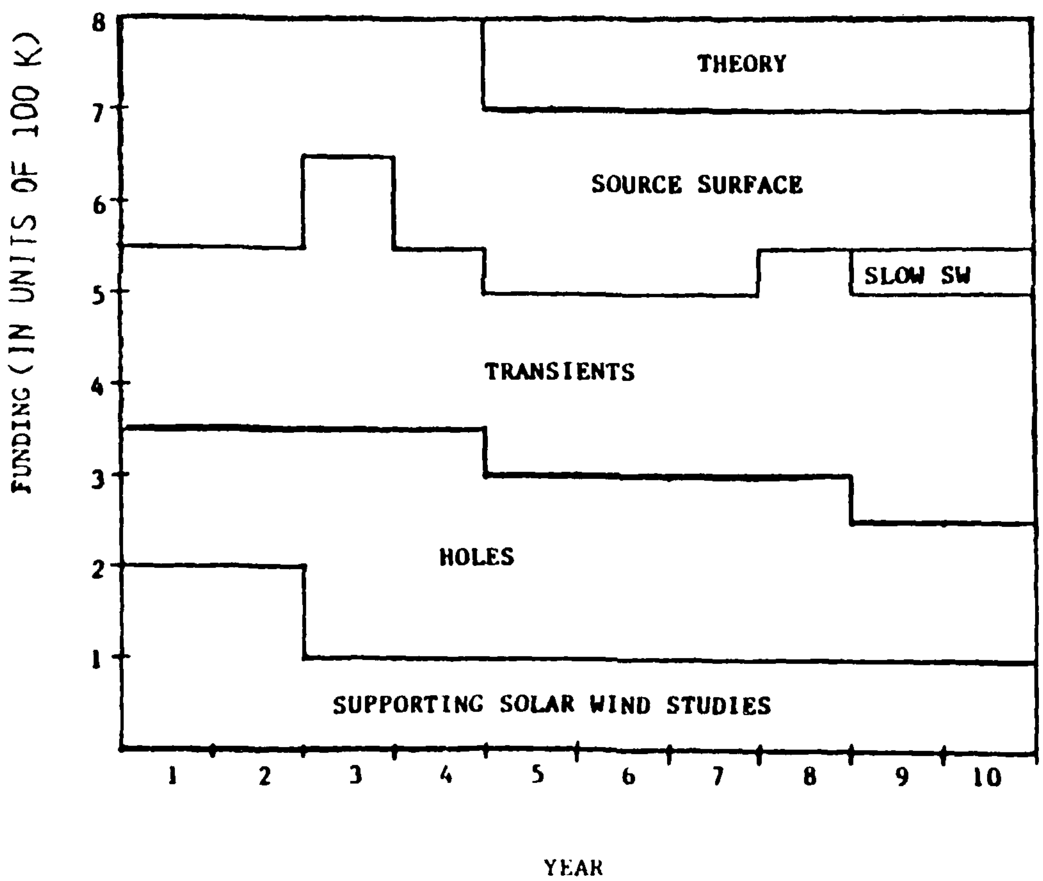


Fig. 1

CORONA-SOLAR WIND COUPLING

DETAILED PLAN (in units of 100 K)

| CATEGORY | ACTIVITY | YEAR 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | sub total | total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Supporting Solar | Sources of $B_Z$ observed in solar wind. | 2 | 2 | 1 | 1 | | | | | | | 6 | 12 |
| Wind | Incorporting results into inter-planetary models. | | | | | 1 | 1 | 1 | 1 | 1 | 1 | 6 | |
| | Ording solar wind properties | 2 | 2 | 1 | 1 | 1 | 1 | 1 | .5 | .5 | .5 | 10.5 | |
| Source | Alfven flux at source surface | .5 | .5 | .5 | .5 | | | | | | | 2 | 19.5 |
| Surface | Estimate of $B_Z$ at source surface (empirical + verification of of models). | | | | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 7 | |
| Slow Solar Wind | Sources and Theory | | | | | | | | | .5 | .5 | 1 | 1 |
| | Role in geoeffective wind | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | .5 | .5 | 9 | |
| Transients | Relationship among flares, prom, and transients | | | .5 | .5 | .5 | .5 | .5 | .5 | 1 | 1 | 5.0 | 22.5 |
| | Description (including accelera-tion) | 1 | 1 | 1 | | | | | | | | 3 | |
| | Modeling | | | .5 | .5 | .5 | .5 | .5 | 1 | 1 | 1 | 5.5 | |
| Holes | Role as sources of fast wind | .5 | .5 | .5 | .5 | | | | | | | 2 | |
| | Behavior this cycle vs earlier | | | | | | | | | .5 | .5 | 1 | |
| | Properties of individual holes vs S.W. | 1 | 1 | 1 | 1 | 1 | | | | | | 5 | 19 |
| | Short lived holes | | | | | | 1 | 1 | 1 | | | 3 | |
| | Self consistant modeling | | | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 8 | |
| Theory | Acceleration of transients | | | | | 1 | 1 | 1 | 1 | | | 4 | 6 |
| | Acceleration of steady solar wind | | | | | | | | | 1 | 1 | 2 | |
| | TOTAL | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 80 | 80 |

Fig 2

CORONA-SOLAR WIND COUPLING

10 YEAR 800 K/yr PLAN

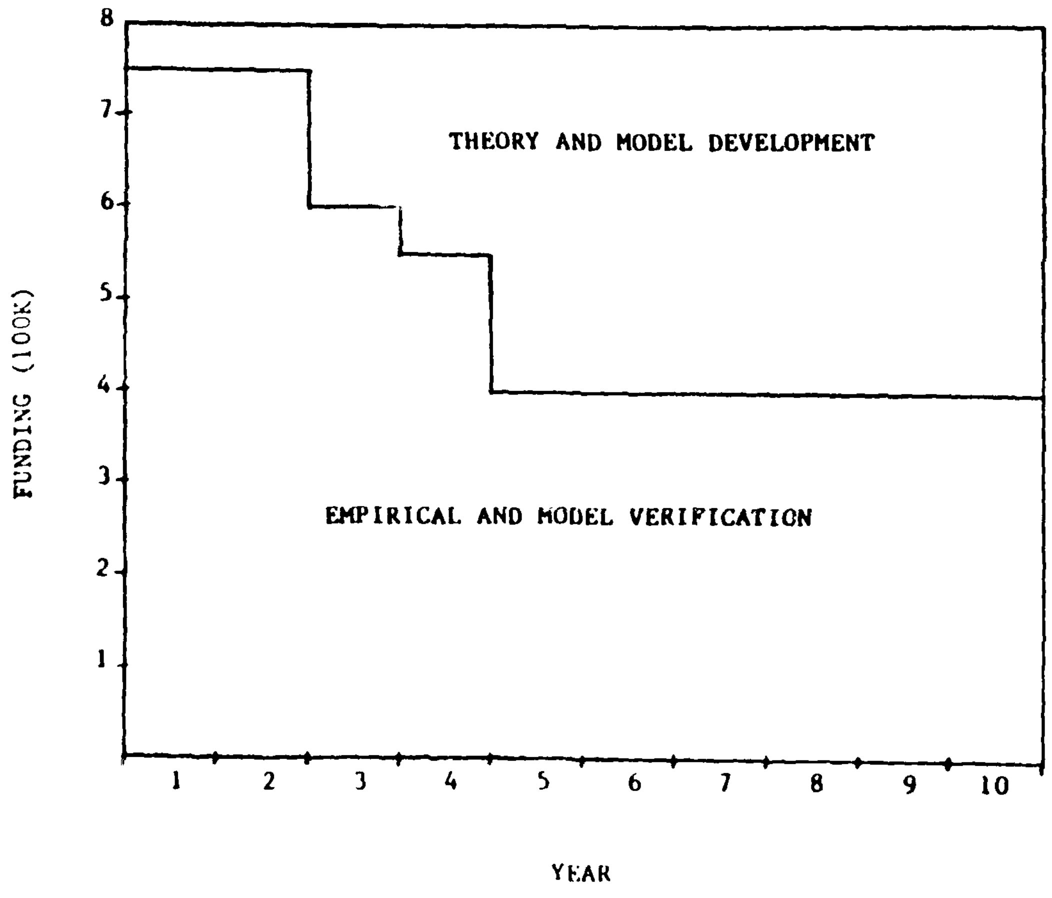


Fig. 3

FIG 4

TOTAL FUNDING LEVEL ( IN K $)

| STUDY | 3yr. PLAN | 10yr. PLAN |
|---|---|---|
| 1 SOURCES OF $B_Z$ | 500 K | 600 K, FIRST 4 YEARS |
| 2 HOLES | 300 K | 500 K, FIRST 5 YEARS |
| 3 TRANSIENTS | 300 K | 900 K, OVER 10 YEARS |
| 4 SLOW WIND | 100 K | 100 K, DURING LAST 2 YEARS |
| 5 CURRENT SHEET | 400 K | 1,000 K, OVER 10 YEARS |